U.S. DEPARTMENT OF COMMERCE
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AD-A032 350

Laboratory Investigation of Undisturbed Sampling of Cohesionless Material Below the Water Table

Army Engineer Waterways Experiment Station Vicksburg Miss

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AD A032350

RESEARCH REPORT S-76-1

LABORATORY INVESTIGATION OF UNDISTURBED SAMPLING OF COHESIONLESS MATERIAL BELOW THE WATER TABLE

by

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October 1976

Final Report

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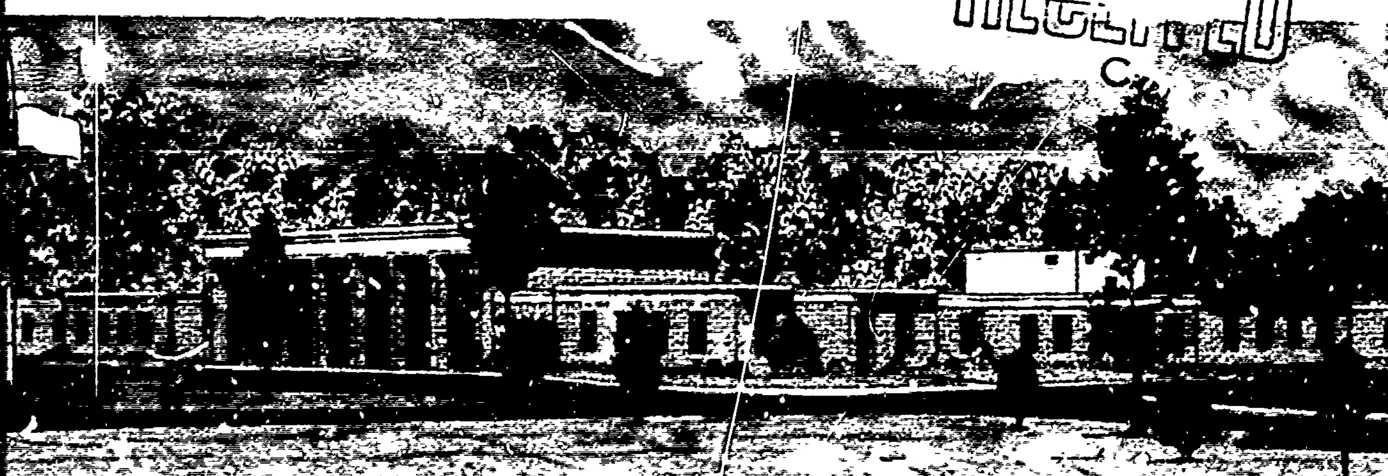

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under CWIS 31145

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Research Report S-76-1	2. GOVT ACCESSION
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): LABORATORY INVESTIGATION OF UNDISTURBED SAMPLING OF COHESIONLESS MATERIAL BELOW THE WATER TABLE	5. TYPE OF REPORT & PERIOD COVERED: Final report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Stafford S. Cooper	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U. S. Army Engineer Waterways Experiment Station, Soils and Pavements Laboratory, P. O. Box 631, Vicksburg, Miss. 39180	10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS: CWIS 31145
11. CONTROLLING OFFICE NAME AND ADDRESS: Office, Chief of Engineers, U. S. Army, Washington, D. C. 20314	12. REPORT DATE: October 1976
	13. NUMBER OF PAGES: 73
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cohesionless soils
Laboratory tests
Sands
Soil test specimens
Undisturbed soil samples

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the results obtained in a laboratory program designed to evaluate the quality of undisturbed samples. A Hvorslev fixed-piston sampler and drilling mud were used to obtain undisturbed sand samples in homogeneously prepared specimens 4 ft in diameter and 6 ft high.

Construction of a homogeneous specimen 4 ft in diameter and 6 ft high is no small feat. Various techniques were used during the course of this study

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20. ABSTRACT (Continued).

for specimen preparation. As-built density determinations indicate that the variation of placed density is approximately -1.5 to +2.9 pcf.

Undisturbed samples 3 in. in diameter were obtained at different overburden pressures. These samples were sealed with end packers and stored overnight in a vertical position. The following day each tube was placed in a horizontal position in a wooden carrying rack, and the top of each tube was marked for orientation purposes. Each tube was then tapped 50 times with a rubber hammer to consolidate the material prior to handling. The tube was then cut into 6-in. segments for laboratory density determinations.

A statistical comparison of the sampled density to the corrected "as built" density was conducted. This comparison indicates that the sampling accuracy is within ±3.4 pcf 95 percent of the time.

PREFACE

The study reported herein was performed by the U. S. Army Engineer Waterways Experiment Station (WES) as part of the Office, Chief of Engineers (OCE), Civil Works Research effort. This investigation was authorized by OCE under the CWIS 31145 work unit entitled "Liquefaction Potential of Dams and Foundations."

WES engineers who were actively engaged in this study were Dr. W. F. Marcuson III and Messrs. W. A. Bieganousky, J. R. Horn, and S. S. Cooper. The work was conducted under the general supervision of Messrs. R. W. Cunny and W. C. Sherman, Jr., former Chief, Earthquake Engineering and Vibrations Division (EE&VD), Dr. F. G. McLean, Chief, EE&VD, and Mr. J. P. Sale, Chief, Soils and Pavements Laboratory (S&PL). This report was prepared by Mr. S. S. Cooper and internally reviewed by Mr. S. J. Johnson, Special Assistant, S&PL. OCE technical monitor for this investigation was Mr. Ralph R. W. Beene.

During the time this study was conducted BG Ernest D. Peixotto, CE, and COL G. H. Hilt, CE, were Directors of WES. The Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
degrees (angular)	0.01745329	radians

LABORATORY INVESTIGATION OF UNDISTURBED SAMPLING OF COHESIONLESS MATERIAL BELOW THE WATER TABLE

PART I: INTRODUCTION

1. Reliable determinations of in situ density of sands below the water table are essential to assess the engineering properties of such materials particularly when liquefaction may be a problem. This problem has become more critical in recent years because more and more structures are being constructed which would cause catastrophic damage and loss of life if they failed. This is particularly true in the case of nuclear power plants and large dams. Because of the critical nature of this problem, the Corps of Engineers felt that the work they had done in this area some years ago should be extended.[1,2] Earlier work conducted at the Waterways Experiment Station (WES) involved development of a means to take undisturbed sand samples using a fixed-piston sampler and drilling mud.[1] Reference 2 describes the results of fixed-piston sampling in a large tank in which sand was placed at variable densities. The density of the sand within the sampling tubes was compared with the placement densities of the sand in the tank.

2. Indirect methods of determining the in situ density have been used widely in the field. Work has been done in this area using indirect methods such as the Standard Penetration Test (SPT) or the Dutch Cone.[3-7] These indirect methods are based on correlations of penetration resistance, overburden pressure, and relative density. They are widely used because they are both expedient and economical means to evaluate in situ density. Many engineers from the start have questioned these correlations; however, they are still widely used. WES is now evaluating the SPT procedure in a stacked ring facility. The results of these tests will be discussed in a subsequent report.

3. In conjunction with the Standard Penetration Tests, WES has taken undisturbed fixed-piston samples in the stacked ring facility. These samples were taken to the laboratory and laboratory density

determinations made. These sampled densities were then compared with the as-built density of the specimens. This report will discuss these results.

PART II: TEST FACILITY

General

4. The major components of the test facility are a 4-ft-diam* stacked ring soil container, a massive, reinforced-concrete foundation, and loading equipment for applying pressure to the top of the soil specimen. The stacked ring container was originally designed for use with a dynamic air overpressure loader,[8] but was adapted to this study. The static pressure equipment used to simulate overburden loading was designed for the purpose. A schematic of the test facility is shown in Figure 1. Figure 2 shows the facility ready for sampling operations. The major components of the test facility as well as the sampling equipment used are described in detail subsequently.

Stacked Ring Soil Container and Foundation

5. The stacked ring soil container was developed from a study conducted by Dr. M. Juul Hvorslev[9] and is similar to a smaller diameter device used at Stanford Research Institute.[10] The WES stacked ring soil container was developed to minimize the wall friction, or silo, effect which is inherent in rigid wall containers and which causes an undesirable reduction in soil stress with increasing container depth. A reduction in stress with increased depth is the reverse of in situ conditions and is particularly significant in rigid wall containers whose frictional effect can reduce the soil stress due to dead weight by as much as 40 percent at a depth equal to the specimen diameter.[11] Stresses from applied loads can likewise be reduced by more than one-half at a depth of one diameter.[11] Hence, the impetus to minimize wall friction effects by means of a vertically flexible container.

6. The WES stacked ring container consists of a stack of 1-in.-high by 4-ft-ID steel rings which are separated with 3/16-in.-thick rubber spacer rings. Container height is controlled by varying the number of rings (steel and rubber) in the stack. Grooves are provided

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

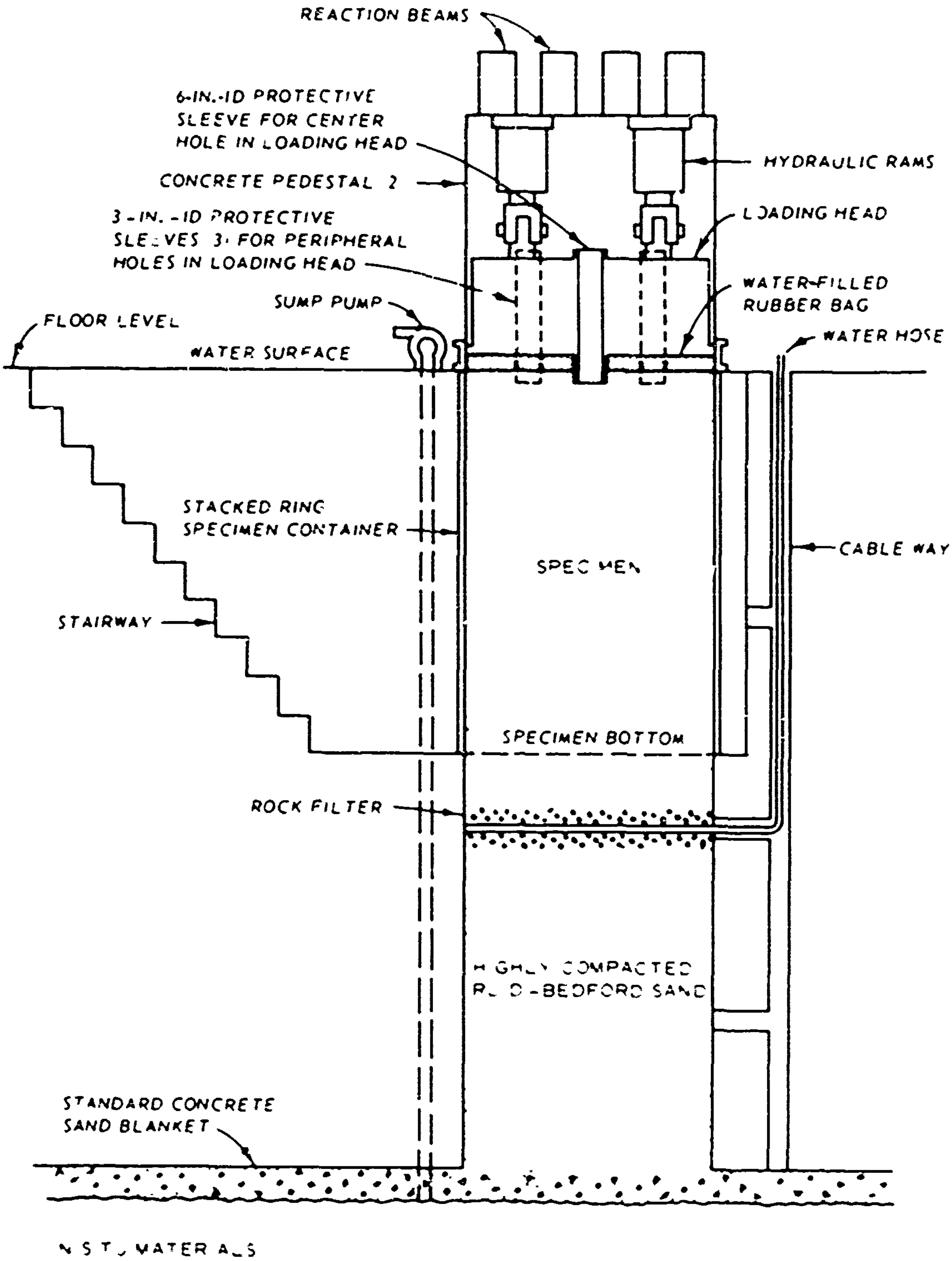


Figure 1. Test apparatus

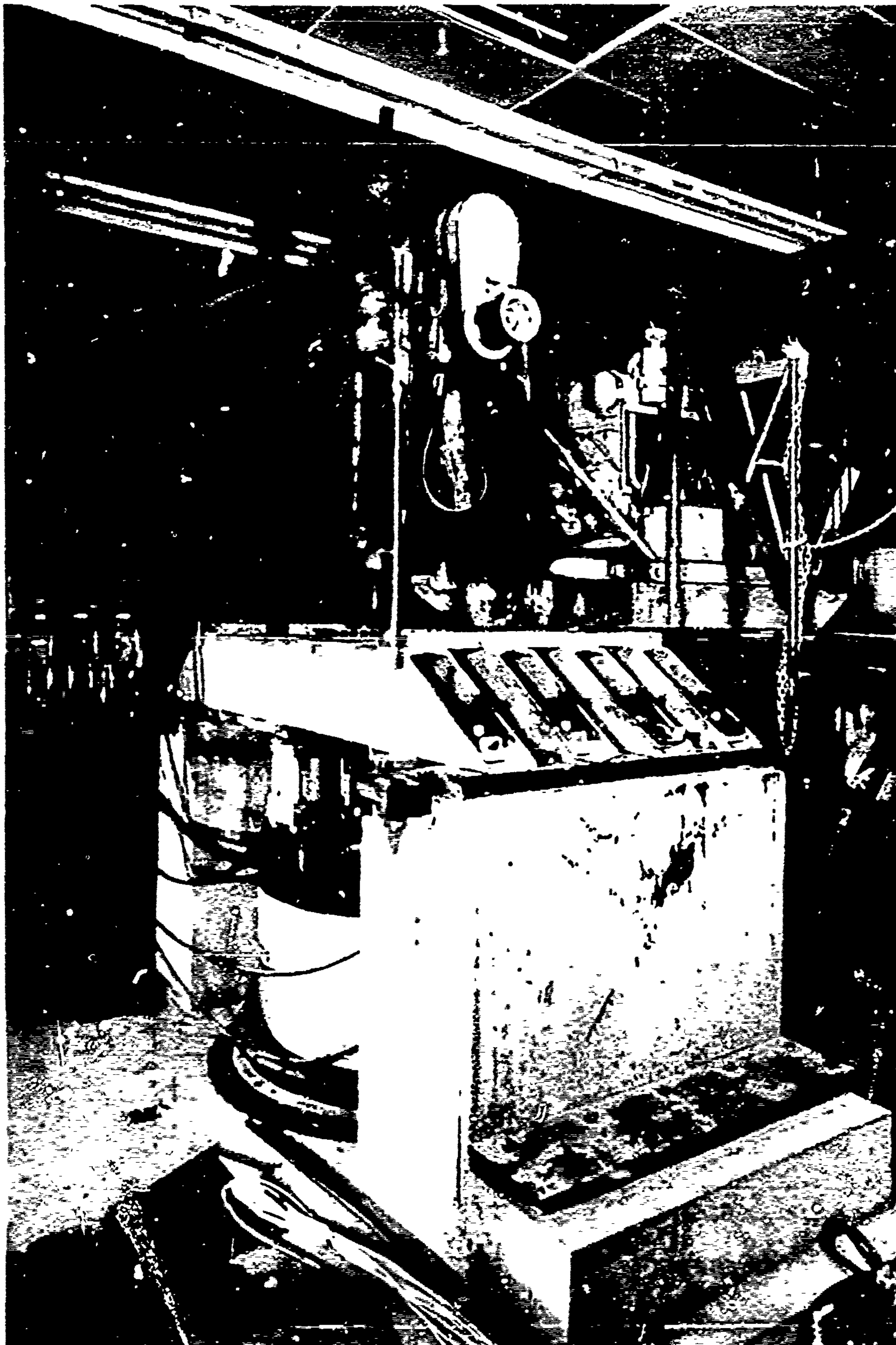


Figure 2. Test facility with drill rig in place

in the steel rings to accept mating keys molded in the rubber spacers. The rubber spacers provide the desired flexibility in the vertical direction while the steel rings serve to restrict radial deformation of the specimen. Calculations based on typical sand specimens indicate that radial deformation should not exceed 0.024 percent for a maximum vertical applied load of 300 psi. This degree of radial restraint is sufficient to provide an acceptably analogous medium for representing field, i.e., uniaxial strain, conditions at depth.

7. During Test No. 4 of this study, micrometer measurements of vertical deformation were made on several rubber spacer rings in the stacked ring container. When the specimen was loaded to 80 psi, each rubber spacer typically compressed 0.0035 in. In subsequent tests, conducted on an empty 2-ft-high section of stacked rings, it was determined that an average deformation of 0.0035 in. corresponds to a vertical load of 750 lb on the container. Thus, the maximum load transmitted to the soil container via soil friction in Test No. 4 is assumed to be 750 lb, or 0.5 percent of the total vertical force of 144,765 lb applied. The remaining load, 99.5 percent of the total load, was transmitted to the specimen. These data clearly indicate that the stacked ring soil container is effective in minimizing wall friction or silo effects.

8. A cross-sectional view of typical steel and rubber rings, showing the nominal unstressed dimensions for each, is presented in Figure 3 For this investigation the stacked ring container was used to confine 6-ft-high sand specimens.

9. The massive concrete foundation of the test facility was designed to withstand the vertical forces developed in dynamically loading 4-ft-diam specimens with overpressures to 300 psi. Consequently, static loadings to 300 psi in this study posed no problems. The top of the main foundation is at floor level with two loader-support pedestals extending 4 ft above the floor. A specimen preparation well is located between the support pedestals and extends from floor level to a depth of 6 ft into the foundation. From the bottom of the specimen preparation well a 4-ft-diam specimen hole extends 6-1/2-ft through the

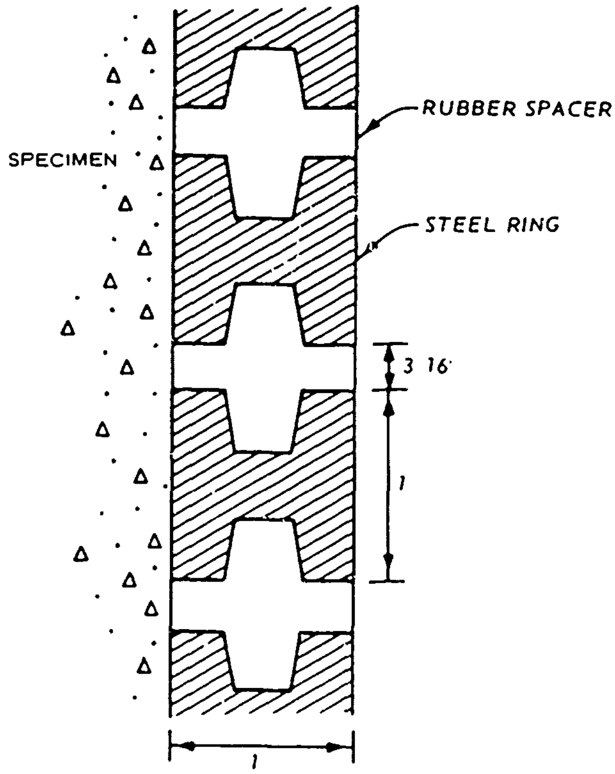


Figure 3. Cross-section view of typical steel rings and rubber spacer rings

foundation to the ground beneath. Approximately 5 ft of this hole was stemmed with highly compacted sand and the upper 1-1/2-ft of the hole was used to install a graded filter so that the test specimens could be submerged from the bottom up. The filter was constructed in three 3-in.-thick layers, grading from a base layer of 1-in.-diam crushed rock to a top layer of "pea" sized rock. A 1/2-in.-diam perforated garden hose was coiled in the base layer of the filter and extended to the floor level via a cableway provided in the foundation. The top filter layer was covered with a single thickness of cotton fabric, and the remainder of the 6-1/2-ft-deep specimen hole was stemmed with compacted sand to the bottom of the specimen preparation pit. The test specimens were constructed over the filter and occupied the 6-ft-deep space between floor level and the bottom of the specimen preparation well, as shown in Figure 4.

Figure 4. Typical specimen in the specimen preparation well

Overburden Loader

10. The overburden loader basically consists of a ram and beam reaction assembly, a cylindrical steel loading head, and a water-filled pressure-equalizing bag. The assembled overburden loader is shown being lowered onto a prepared specimen in Figure 5. Vertical load is applied to the loading head by the hydraulic rams. The water bag is placed between the loading head and the specimen, and serves to uniformly distribute the vertical load applied to the specimen.

11. The beam assembly consists of four steel box members which were welded to crossmembers into a single unit. Three double-acting 8-in.-diam hydraulic rams were welded to the bottom of the beam assembly

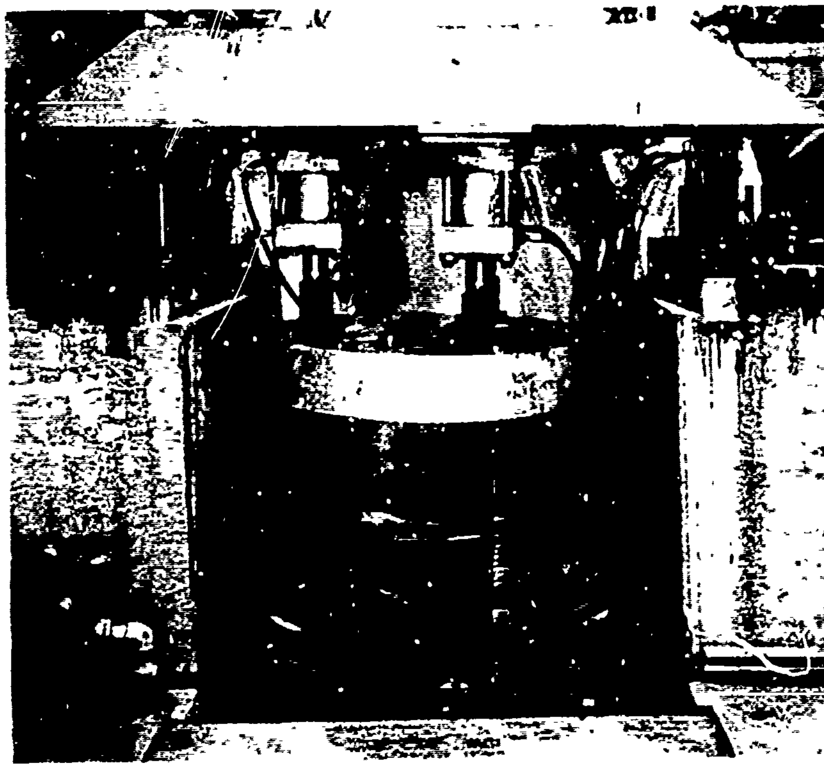


Figure 5. Overburden loader being
lowered onto specimen

so that the cylinder end of each ram is founded on two beams. The rams are individually driven by three manually operated hydraulic pumps mounted on a portable console, shown in Figure 6. Hydraulic pressure delivered to each ram is monitored with console-mounted bourdon gages.

12. The overburden head is an internally braced 46-in.-diam by 18-in.-high hollow steel cylinder. Its bottom surface is a machined 48-in.-diam flange which contains a peripheral "O" ring seal. As shown in Figure 7, three 3-in.-ID and one 6-in.-ID steel sleeves penetrate the loading head vertically. These sleeves extend through holes provided in the water bag and penetrate approximately 2 in. into the specimen beneath. They serve to guide the samplers and to protect the water bag during sampling and reaming. The fiberglass-reinforced rubber water bag, shown in Figure 8, is nominally 48-in.-diam by 3-in.-thick, and is filled by two tubes which extend upward through holes provided in the

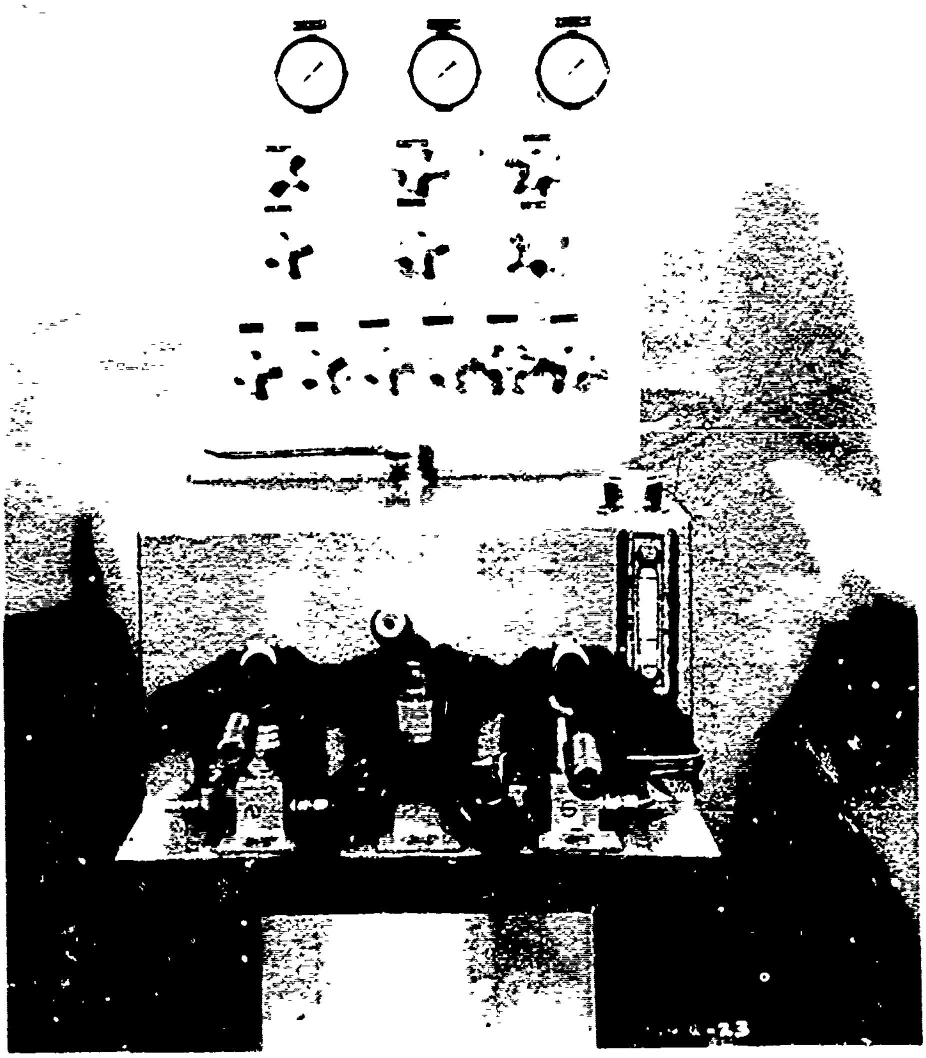


Figure 6. Control console

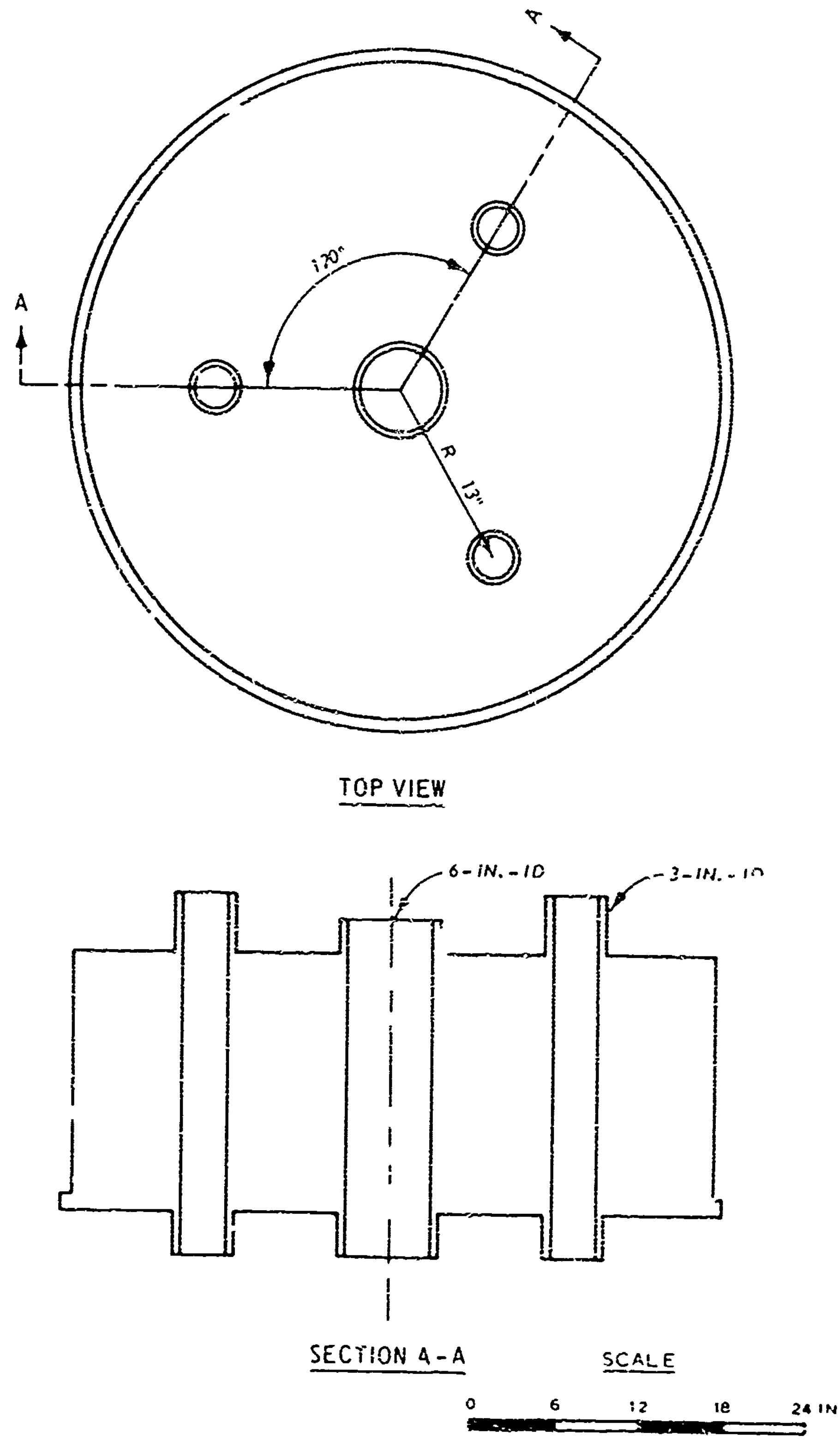


Figure 7. Location of steel sleeves in loading head

Figure 8. Fiberglass-reinforced water bag

loading head. Bag pressure, or vertical stress applied to the specimen, is measured with a calibrated bourdon gage connected to the filler tube. When in the loading position, the bag is confined radially by a 6-in.-high, machined steel collar which rests on, but is not attached to, the top steel ring of the stacked ring container. The "O" ring seal in the flange of the loading head prevents metal to metal contact with the collar. With this arrangement, no live vertical load is applied directly to the stacked ring container, although some vertical load is transmitted to the rings via soil friction.

Sampling Equipment

13. The drill rig used in this study is a commercially available, skid-mounted Acker Teredo Mark II Soil Sampling Drill. Low overhead clearance in the laboratory precluded the use of a derrick, so lifting

tackle for the drill rods was secured to rafters in the ceiling. For sampling and drilling, the rig was elevated on a platform built level with the top of the loader-support pedestals. A portable mud pump supplied with mud from a sump atop the loading head provided mud circulation during reaming. The mud sump was formed by encircling the upper part of the loading head with a thin metal band, as shown in Figure 9.

14. Undisturbed samples were taken with a Hvorslev[12] 3-in.-ID thin-wall, fixed-piston sampler. Nominal dimensions for the 16-gage sample tube include a 2.97-in.-ID cutting edge, a taper angle of 10 degrees on the cutting edge, and an area ratio of 11 percent.[13] The complete sampler is shown in Figure 10, and a schematic of the sampler is shown in Figure 11. The drill rod used in sampling was 2-in.-OD "N" size. The WES-modified fishtail bit shown in Figure 12 was used for reaming. The bit itself is commercially available. However, special baffles were added at WES to direct the flow of drilling mud upward, away from the bottom of the borehole. Thus, disturbance of the underlying material by circulating mud is minimized when reaming or drilling to sampling depth.

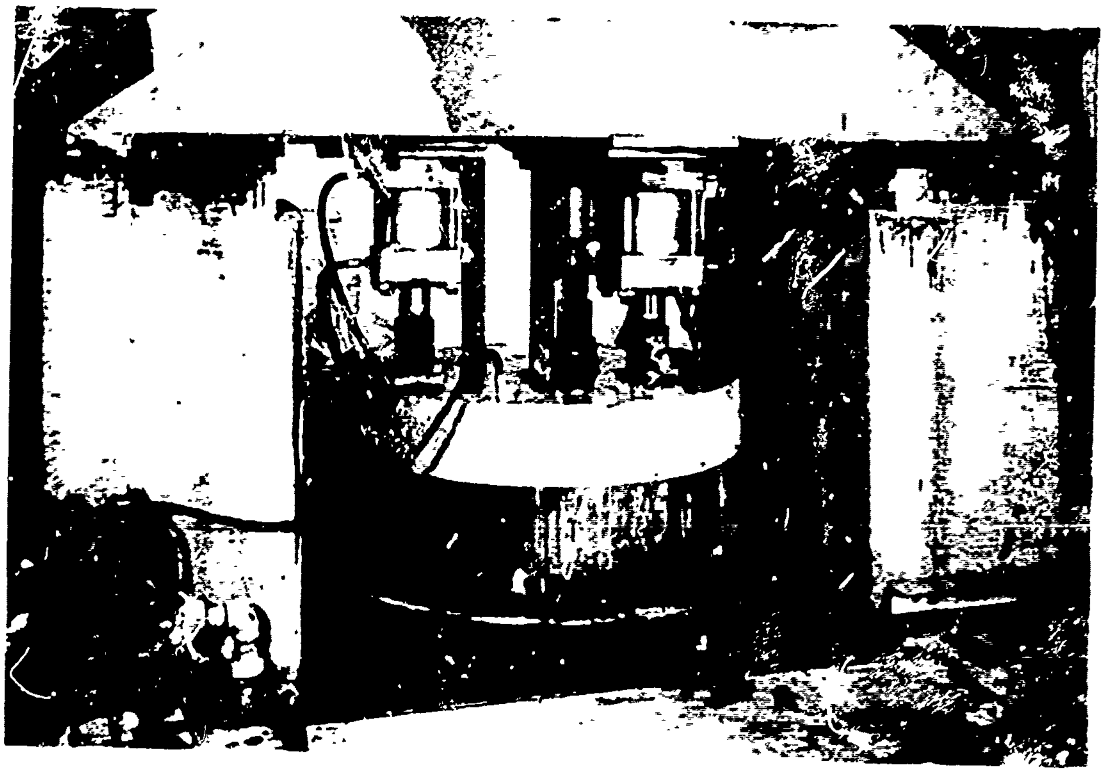


Figure 9. Mud sump atop loading head

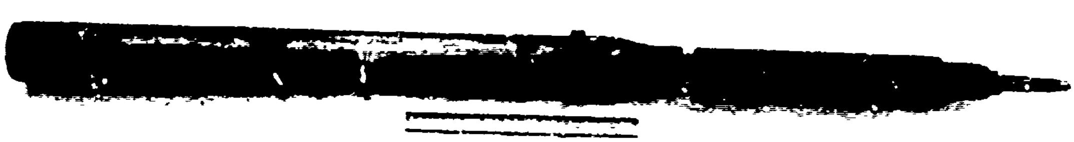


Figure 10. Hvorslev 3-in. fixed-piston sampler

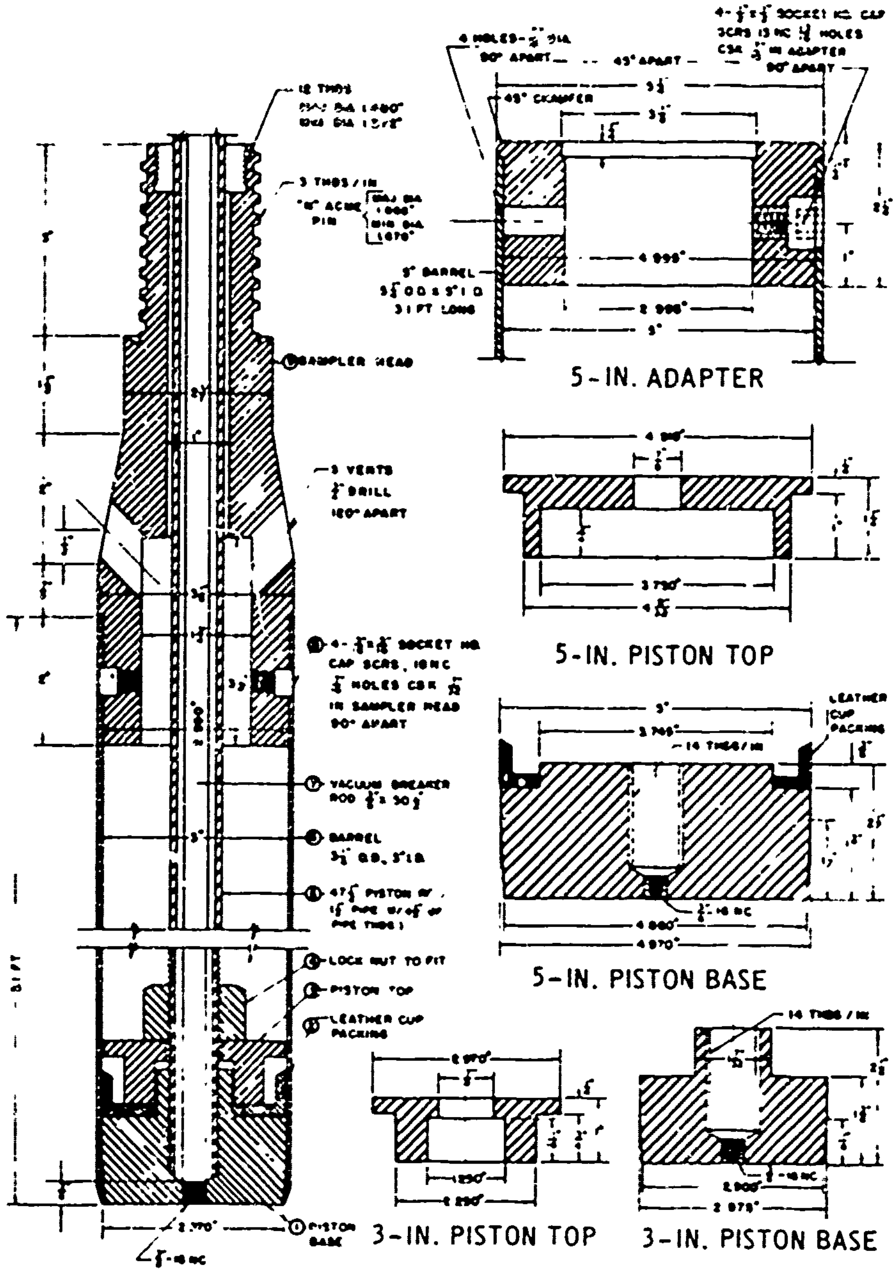


Figure 11. Hvorslev-type 3-in.-diameter fixed-piston sampler with 5-in. adapter. (U. S. Army Engineer Waterways Experiment Station drawing No. 1295-3, revised 9 Oct 53)

Figure 12. WES-modified fishtail bit

PART III: TEST PROGRAM

General

15. The test program consisted of undisturbed sampling and standard penetration testing on seven 4-ft-diam submerged specimens of a locally available sand. Results of the penetration testing will be reported separately and only the undisturbed sampling will be described herein. In the course of the study 24 undisturbed samples were obtained from specimens placed at relative densities, D_r, ranging from 18 to 60 percent.

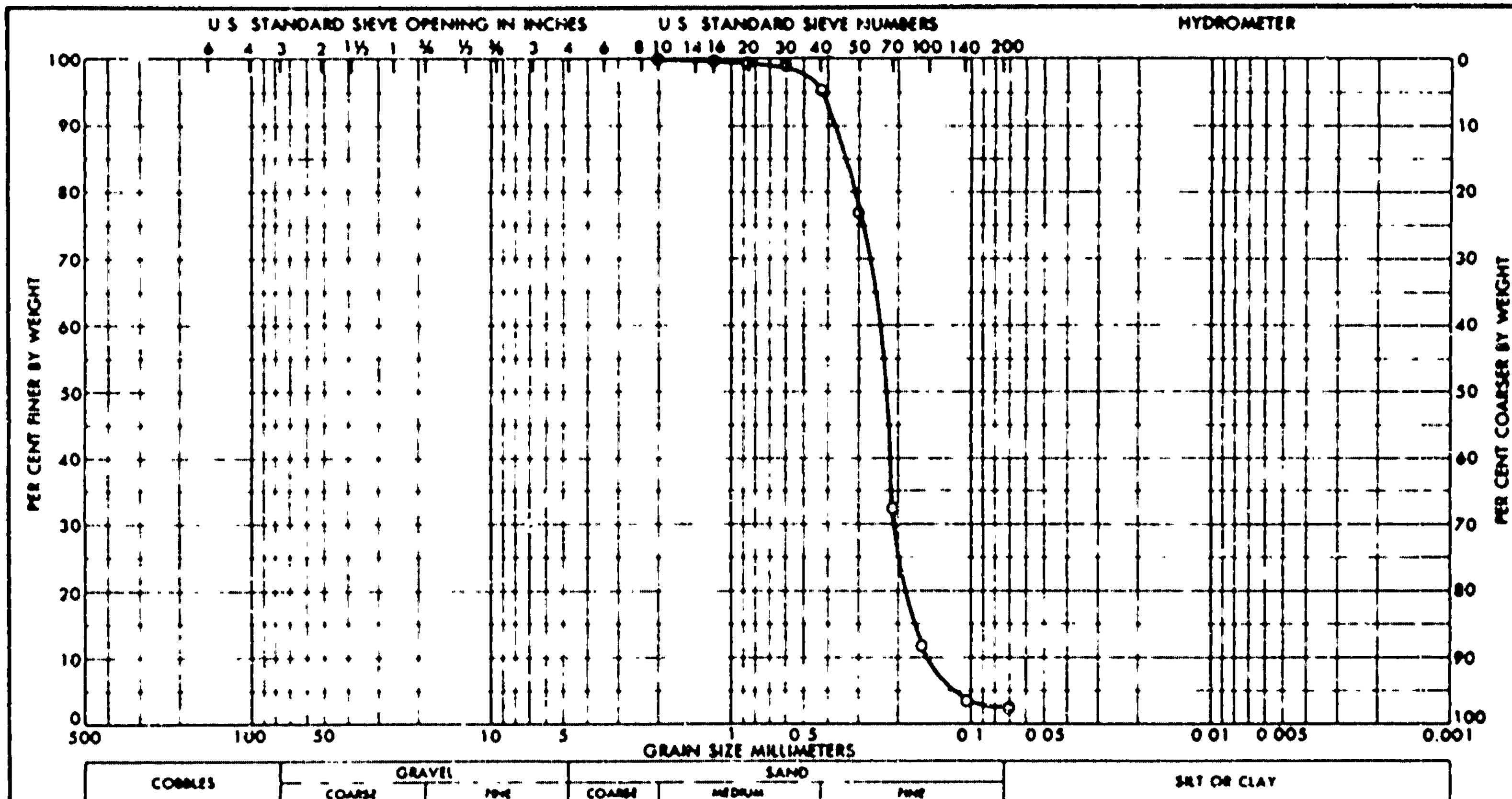
Material Properties

16. The material used in this study is commonly termed Reid-Bedford Model Sand and its properties have been well documented in previous studies conducted at WES. However, a further series of material property tests was conducted for this investigation using procedures outlined in EM 1110-2-1906.[14] These tests included determinations of maximum and minimum dry density, compaction, and gradation. Typically, maximum and minimum dry density were 107.1 and 88.7 pcf, respectively. A representative gradation curve for the material is shown in Figure 13. In addition, a petrographic examination was performed on the sand. Results of this examination are presented in Appendix A.

17. Based on these data, Reid-Bedford Model Sand is characterized as a uniform, fine sand (SP) comprised predominantly of subrounded to subangular particles.

Specimen Preparation

18. Specimens were placed in the stacked ring container by raining. A rotating sand rainer was used to construct the first four specimens in the test program; however, it was not possible to build a specimen of low relative density (i.e., $D_r < 35$ percent) with this rainer. A second sand rainer of similar design, shown in Figure 14, was built to provide a wider range of relative density. It was used to



SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
BAG		SAND (SP)				
		TAN				
		Gs 2.65 (est)				

LIQUEFACTION TESTS
REID BEDFORD MODEL SAND
1 AUGUST, 1974

Figure 13. Typical grain-size distribution curve for Reid-Bedford Model Sand

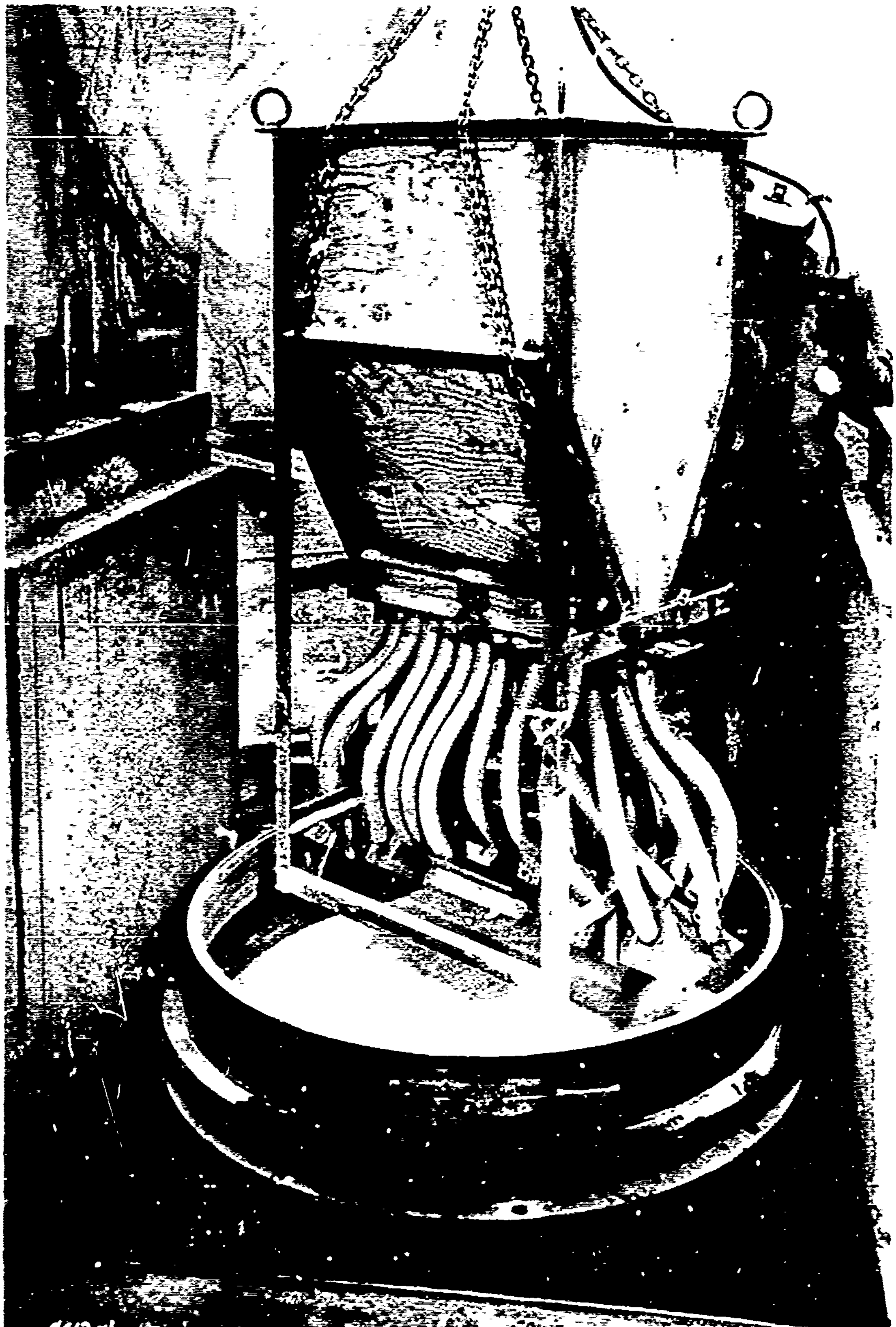


Figure 14. Rotating sand rainer

place the remaining specimens. The two rainers differ principally in the number and arrangement of flexible tubes and in the diffuser plate incorporated in the second rainer. The diffuser plate facilitated adjusting the sand flow so the second rainer produced a more level specimen surface. With this rainer. density is primarily controlled by regulating the free fall distance between the diffuser plate and the specimen surface. A relative density as low as 18 percent was achieved with Specimen No. 5.

19. Specimen construction was begun by first filling the rainer reservoir with enough sand to produce a 6-in.-thick specimen lift. Then, the rainer was lifted and suspended at the desired height above the specimen by an overhead traveling crane, lift density was controlled by varying the height of drop from the rainer to the specimen surface. In general, higher densities required greater heights of drop. The rainer was rotated at approximately 15-20 rpm during raining to evenly distribute the sand over the specimen surface. This placement procedure was repeated for successive lifts until a 6-ft-high specimen was built. When the last lift was placed, the specimen surface was screeded level with the top of the stacked ring container.

Test Procedures

20. Finally, the specimen was submerged from the bottom up by admitting water to the perforated hose coiled in the filter beneath the specimen. The water flow through the hose was controlled so the water level in the specimen preparation pit rose from 3 to 6 in. per hour. The stacked ring container and preparation pit are connected by a cableway in the foundation and the stacked ring container is permeable so the water tended to rise simultaneously in the specimen and pit. As the water level rose, some air was observed to escape from the specimen by bubbling through the walls of the stacked ring container at ring-gasket interfaces.

Density measurements

21. Density measurements for the first four specimens consisted

of weighing the material placed in each lift and then computing an overall density after the final lift was placed. To evaluate placement uniformity, incremental density measurements were taken in the remaining specimens using a WES-developed box density device.[15] The box density device is shown in use in a typical specimen in Figure 15. Generally, box density measurements were made in each 6-in.-thick lift placed.

Overburden loading

22. In preparation for testing, the overburden loader was assembled atop the specimen. Assembly was begun by fitting the overburden head with a deflated water bag and then lowering it into the 4-ft-diam by 6-in.-high steel ring used to confine the periphery of the water bag, as shown in Figure 5. The loading head was positioned within 3 in. of the specimen surface and water was introduced into the bag until it filled this space. This completed the assembly process, and permitted the application of overburden pressure simply by pressuring the rams.

23. Overburden pressures of 10, 40, and 80 psi were used in the test program. A diagram of the typical loading sequence applied to the test specimens is shown in Figure 16. Horizontal leveling of the loading head was accomplished by individually pressurizing the hydraulic rams. Each pressure increment applied was maintained for approximately 30 minutes prior to sampling so pore water pressure could dissipate and conditions within the specimen could stabilize.

24. During testing there was some variation in overburden pressure applied as a result of the penetration, sampling, and reaming. Typically, the gage monitoring overburden pressure indicated a 1-psi drop for each 18-in. drive during penetration testing, and an additional 3- to 5-psi decrease when the splitspoon was withdrawn from the specimen. After the splitspoon was withdrawn, pressure was restored to the desired level. During reaming, the applied pressure dropped approximately 1 to 2 psi, and after withdrawal of the undisturbed sampler tube the pressure dropped about 2 to 5 psi. In both instances pressure was restored to the desired level before continuing the test.

Figure 15. WES box density device in use on a typical specimen

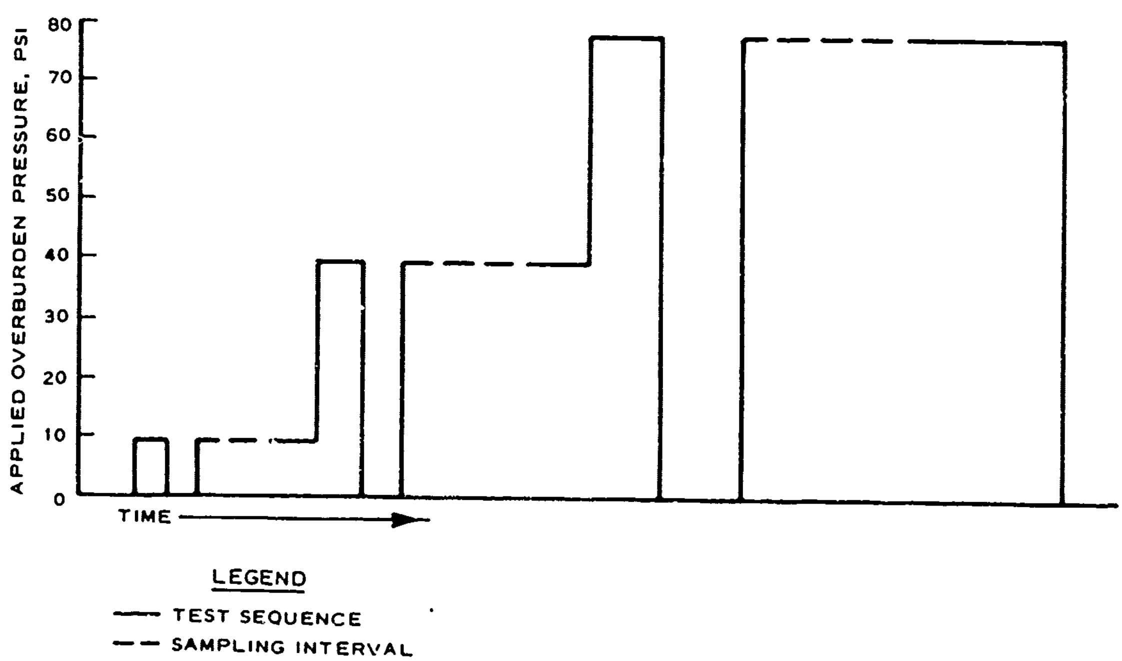


Figure 16. Typical load-time history

Undisturbed sampling

25. Undisturbed sampling was conducted in conjunction with standard penetration testing. The sampling was to be done in stages to conform with the penetration tests planned, and all of the undisturbed samples were taken through the center hole in the loading head and along the cylindrical axis of the specimen. Sampling was originally planned at overburden pressures of 10, 40, and 80 psi; however, this often proved to be impossible because the drill rig employed did not develop sufficient force to drive the sampler at pressures greater than 10 psi. Consequently, most of the undisturbed 3-in.-OD samples were taken with 10 psi applied to the specimen. After each sampling operation, the center, or sampling, hole was stemmed with pipe before penetration tests were conducted in the peripheral holes. This practice was adopted to prevent hole closure and concomitant reductions in lateral pressure.

26. The test sequence was generally as follows:

- a. With 10-psi pressure applied, the first tube was driven 2 ft into the specimen through the center hole in the loading head. After withdrawal, the center hole was stemmed with pipe to 2 ft in depth.
- b. Splitspoon tests were conducted in a peripheral hole to a total depth of 6 ft, after which the peripheral hole was stemmed.
- c. The stemming pipe was withdrawn from the center hole and the overburden pressure was raised to 40 psi. Next, the hole was reamed to a depth of 2 ft and the second undisturbed sample was taken from 2 to 4 ft in depth (by temporarily reducing the overburden pressure applied, if necessary). Afterwards, the hole was stemmed to 4 ft in depth.
- d. Penetration tests were conducted in the second peripheral hole as per step b, above.
- e. The last undisturbed sample was taken from 4 to 6 ft in depth as described in step c except that, conditions permitting, the last sample was driven with 80-psi overburden pressure applied to the specimen.
- f. Penetration tests were conducted in the third peripheral hole, concluding the test.

27. Sampling and incremental density determinations were carried out in accordance with procedures outlined in references 12 and 13. The

undisturbed samples were sealed with end packers and stored overnight in a vertical position. The following day, the tubes were placed in a horizontal position in a special wooden carrying rack. The top of each tube was marked so that this orientation could be maintained throughout the density determinations. Each tube was then tapped 50 times with a rubber hammer on the top surface to consolidate the sand (25 blows in one direction, repeated in the opposite direction along the tube). The tubes were later cut into 6-in. segments for density determinations. Density determinations were also made on shorter sections if enough additional material remained after the tube was cut into 6-in. segments.

Test Results

28. A total of 71 incremental density determinations were made on 24 undisturbed samples. These data, together with placement densities, are shown in Plates 1-7 for each test conducted. The placed and sampled dry density results are plotted versus depth in the specimen. A scale of relative density, D_r , is also provided at the top of each plot. Each sampled density increment is identified by two numbers, for example 1-3. The first number indicates the sequence in which the samples were taken, i.e., the number one denotes the first sample taken. The second number indicates the tube increment from which the density determination was made; in this instance the third increment. The symbols for incremental density are scaled to represent the length of the tube increment from which the density determination was made.

29. In each plate, the variation of sampled density from placed density is also plotted versus depth. Note that a density variation is plotted only for those sample depths where both a placed density and a sampled density were available. Based on this criterion, a total of 65 density variations have been plotted. The density variations plotted for specimens 2 and 4 constitute a special case because the average placed density shown for these specimens was obtained from total weight and volume measurements rather than incremental box density measurements. These specimens were built early in the study when placement

techniques were being developed and the problem of vertical density variations had yet to be addressed. These data, comprising 22 of the 65 density variations plotted, have been included only for gross comparisons since the implicit assumption of an average (uniform) vertical density is known to be incorrect. Negative values on the plots indicate that the sampled density determination showed a lower density than the placed density; positive values indicate the reverse. Various factors which affect the comparison of placed and sampled densities obtained in the study will be examined in the analysis section of this report.

30. Also shown in the plates, where applicable, are plots of force on the sampler versus depth of penetration. These data were computed from drill-rig, hydraulic pressure measurements recorded for each 6 in. of penetration during sampling. To compute the force applied to the sampler, the rig hydraulic pressure was multiplied by the total working area of the two hydraulic rams pushing the sampler. When pushing the sampler in dense material, the rig pressure frequently exceeded the range of the bourdon gage used to make the pressure measurements. The maximum force of 6300 lb shown in plots may thus be substantially less than the actual force applied to the sampler. Sampler force is plotted as a dashed line to indicate some uncertainty in accuracy.

PART IV: ANALYSIS

Variables Which Affect the Test Results

31. It is obvious that an assessment of sampling accuracy is no better than the accuracy with which specimen conditions can be determined at the time of sampling. Given the nature of soil materials and the current state of the art in soil measurements, it is equally obvious that test results will be accurate only to within certain limits. Accordingly, it is necessary to evaluate by the most practical means any variables which are believed to influence test results significantly. Considering the test procedures employed in this investigation, the most significant variables to be evaluated before sampling accuracy can be assessed are:

- a. Accuracy of box (placed) density measurements.
- b. Uniformity of specimen density at the depth of measurement.
- c. Placed density variations due to the overburden pressures applied.

32. The first variable, i.e., the relative accuracy of the box density measurements, has been documented on dry, Reid-Bedford sand in earlier studies.[15] Based on these studies, the box density measurements made are believed to be accurate within ±0.2 pcf.

33. The second variable, uniformity of specimen density, was initially considered only in terms of vertical variations. It was desired to monitor specimen density control by an expedient means so box measurements of lift density were undertaken. In the course of later testing, it was found that placed density also varied laterally by a maximum of about ±3 pcf from center to edge of the specimen.[16] This condition is believed to have resulted from using a rotating sand rainer to place the specimens. Improved methods for placing the sand have since been developed and will be reported separately.[16] Nevertheless, it is believed that all of the specimens reported herein suffered some lateral variation in density from the center (where the sample was

taken) to the radius of the peripheral holes (between which the box density measurements were made). It is probable, then, that the placed densities reported did not accurately reflect densities where the samples were taken, and that the variation was typically on the order of ±2 pcf.

34. A direct measurement of specimen deformation would have provided a convenient way to assess the third variable, placed density increase due to overburden pressure. This change in density is not otherwise accounted for because placed density was measured before overburden pressure was applied and the samples were taken later. Unfortunately, measurements of specimen deformation under load were not conducted during this study because the physical arrangement of the test apparatus is ill suited to the purpose. Also, the absence of a rigid boundary at either end of the specimen may adversely affect the accuracy with which such measurements could be made. Nevertheless, it is recognized that density changes occur as a result of loading, and that sampled densities should properly be compared with placed densities corrected to reflect the change. In order to indirectly assess the significance of density changes under load, one-dimensional consolidometer tests were conducted on saturated samples of Reid-Bedford sand. Results from these tests are shown in Figures 17, 18, and 19 and these results were used to derive the correction curves shown in Figure 20 which relate placed density and density increases to overburden pressure applied. The density corrections derived, the variations between placed density (corrected and uncorrected) and sampled density for each test, and other pertinent data are summarized and tabulated in Table 1. The density corrections for overburden pressure applied ranged from 0.19 to 1.82 pcf, and averaged about 0.7 pcf. The correction values postulated should be reasonably accurate, considering the method of derivation and its applicability to test conditions.

35. To summarize, the three variables and their probable influence on the accuracy of placed density determinations are as follows:

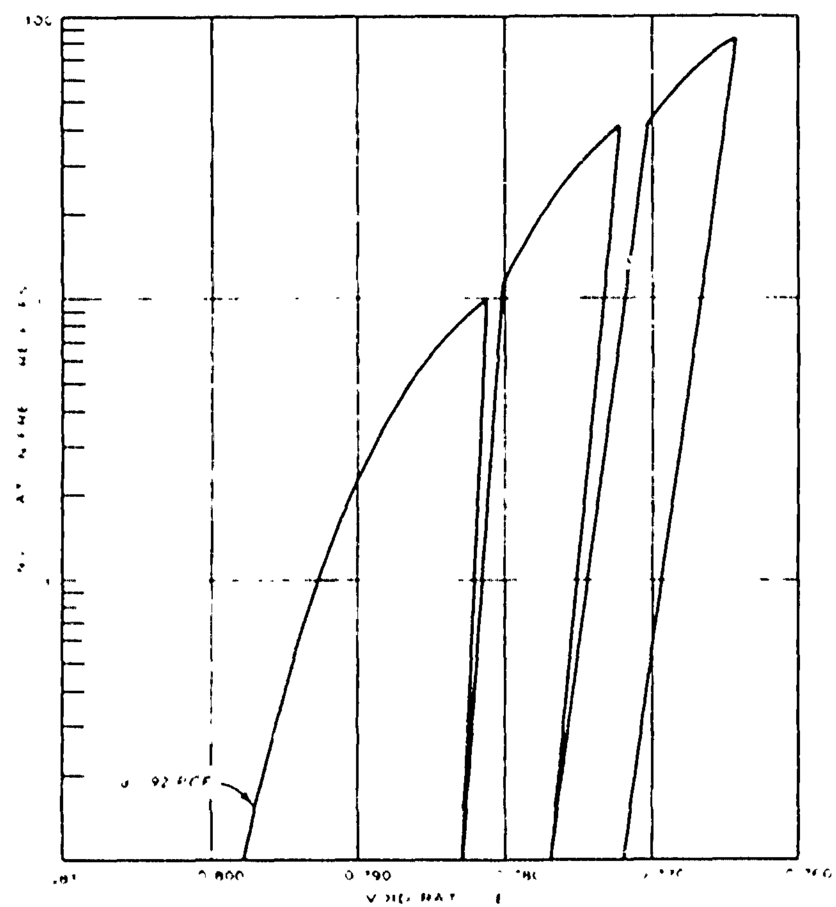


Figure 17. Consolidation test results on a submerged Reid-Bedford sand specimen which was placed at a dry density γ_d = 92 pcf

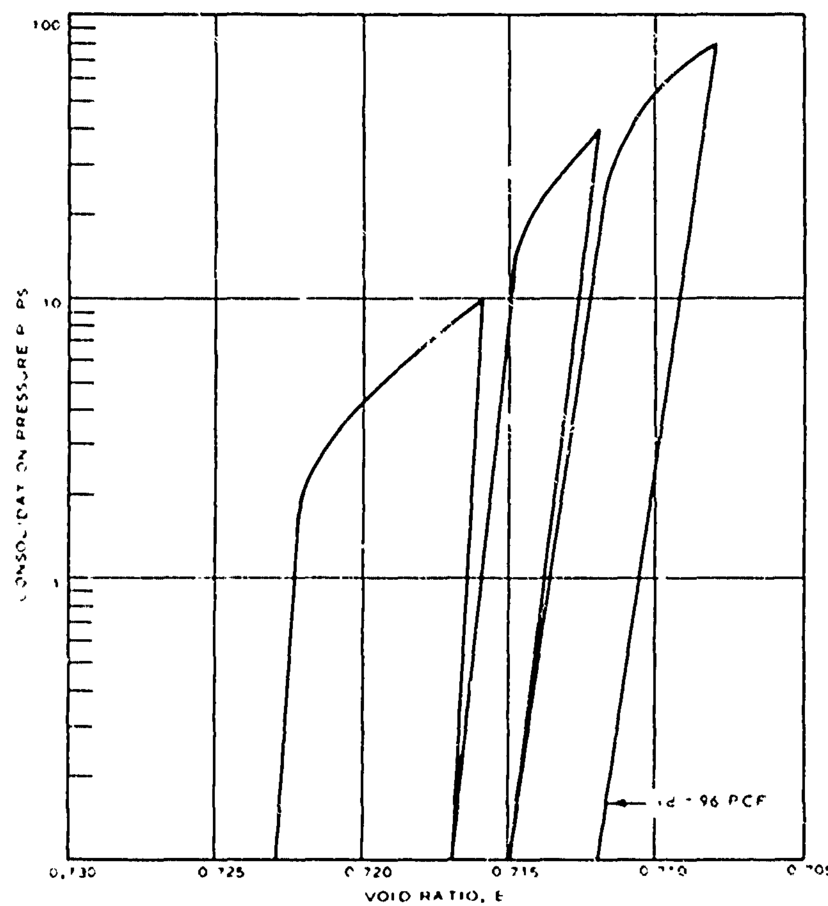


Figure 18. Consolidation test results on a submerged Reid-Bedford sand specimen which was placed at a dry density γ_d = 96 pcf

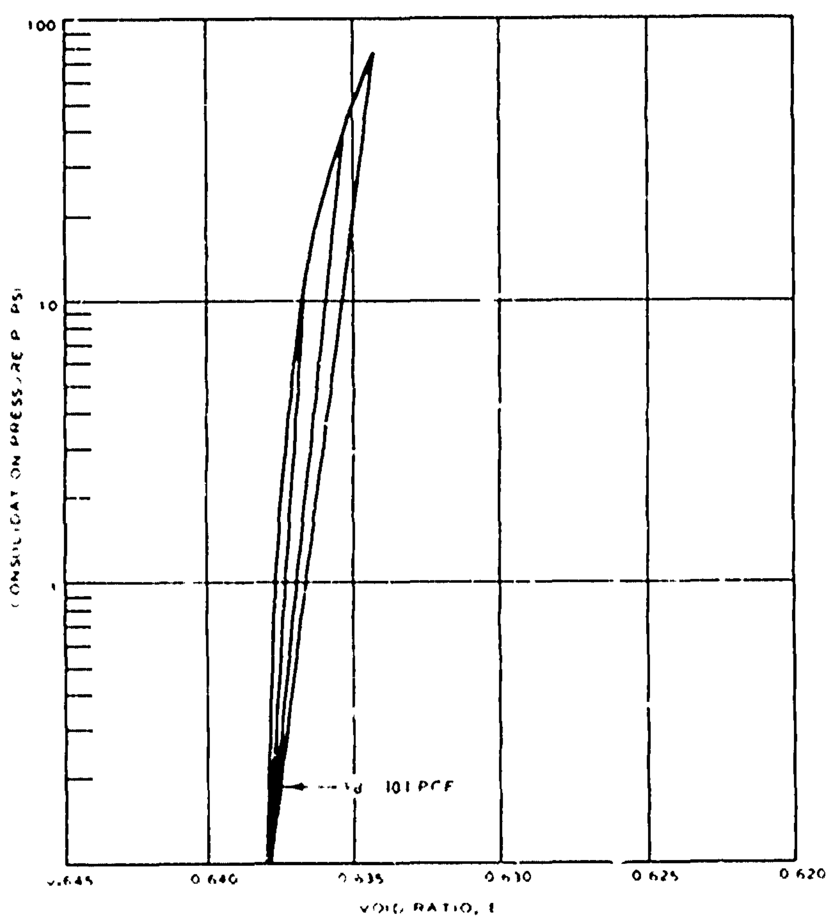


Figure 19. Consolidation test results on a submerged Reid-Bedford sand specimen which was placed at a dry density γ_d = 101 pcf

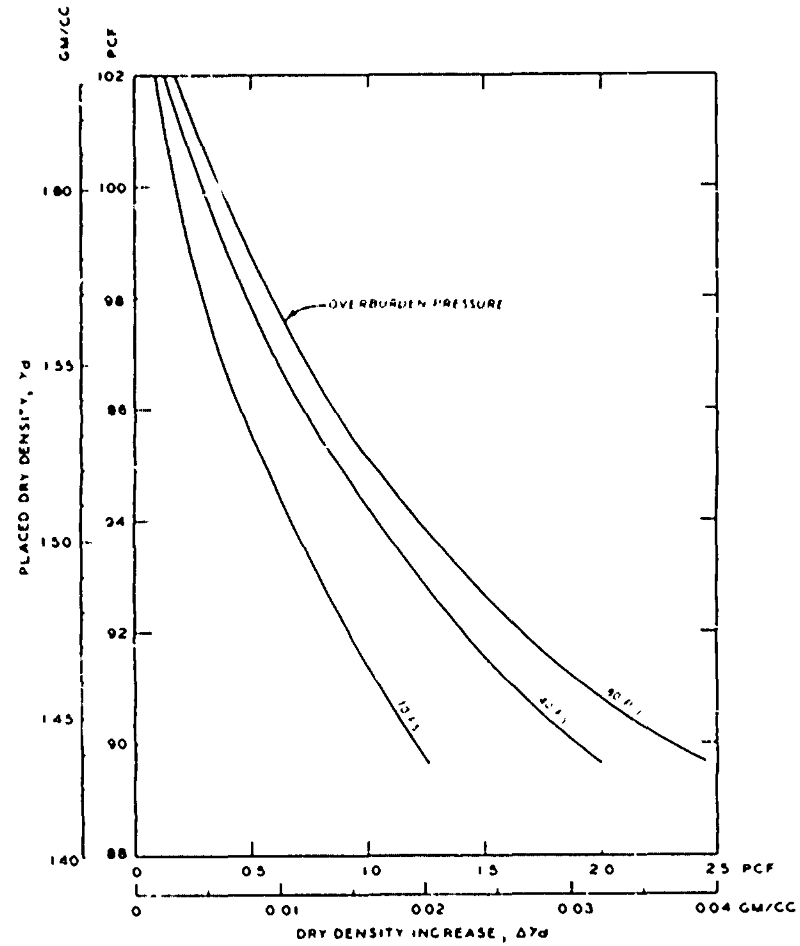


Figure 20. Density increase of Reid-Bedford sand for overpressures of 10, 40, and 80 psi

Variable	Probable Range of Variation pcf
Box density measurement error	±0.2
Specimen nonuniformity	±2.0
Density change due to overburden pressure	+0.7 pcf (average)

The cumulative upperbound error from all three variables would thus be +2.9 pcf and the corresponding lowerbound error would be -1.5 pcf. The positive (+) bias is assumed to represent overburden pressure effects.

Comparison of Placed and Sampled Density Results

36. The data presented in Plates 1-7 and summarized in Table 1 were used to make a gross comparison in the form of the distribution plot shown in Figure 21. The ordinate of the plot in Figure 21 shows frequency of occurrence of a given density variation out of the 65 density variations obtained. The abcissa of the plot is variation from placed dry density in both pcf and gm/cc units. Density variations were rounded off to the nearest 1/2 pcf (0.008 gm/cc) before plotting. The arithmetic mean of the 65 density variations is 1.1 pcf (0.016 gm/cc); this is consistent with the assumption of positive (+) bias from overburden pressure effects. The standard deviation is 1.7 pcf (0.0271 gm/cc). Two of the density variations recorded, those at -6 and -10 pcf, respectively, are certainly suspect and were not considered in the calculations. While no specific reason can be cited, it is assumed that the samples in question were inadvertently disturbed during either the cutting or measurement processes.

37. The erratic portions of the plot shown in Figure 21 are at least partly due to the limited data population obtained; however, it is also probable that the test variables described previously have some effect as well. To investigate the data trend over a range of placed densities a second plot was prepared as shown in Figure 22. In Figure 22, placed dry density is plotted on the abcissa and the incremental sampled density is plotted on the ordinate. Relative density scales are also pro[illegible] for reference on both axes. Only the data from

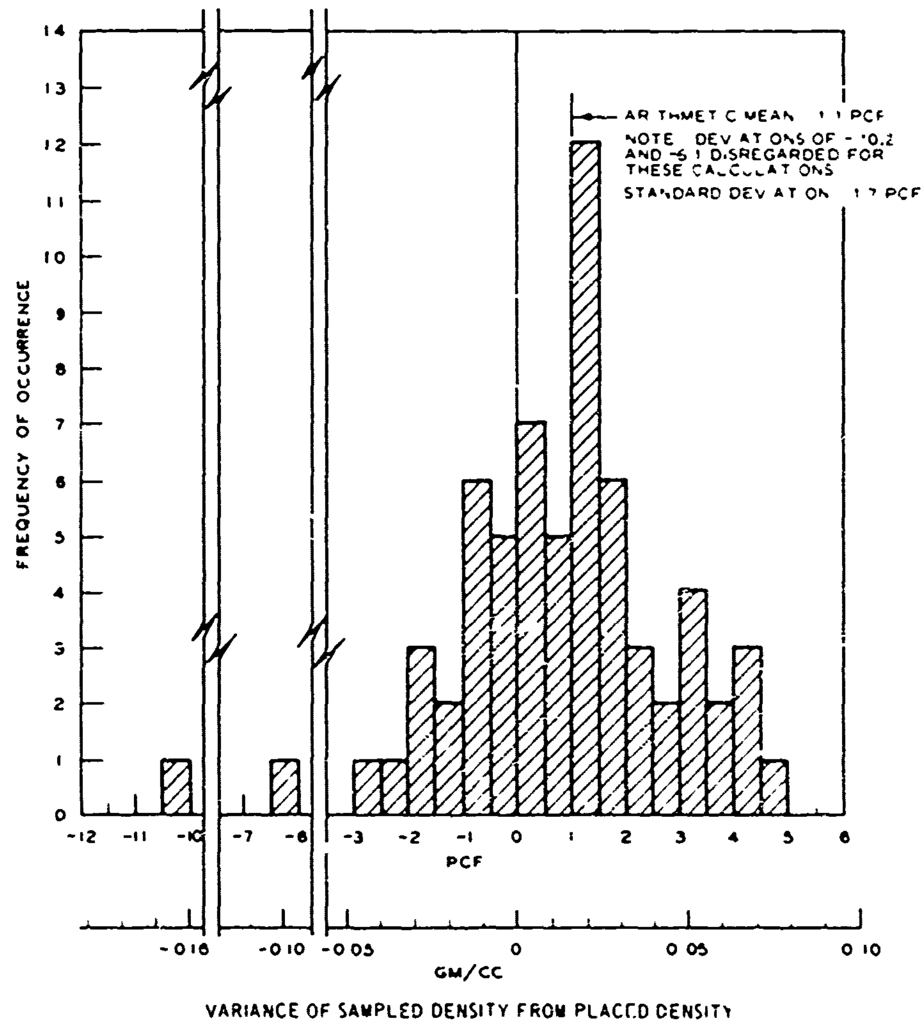


Figure 21. Distribution of density variations

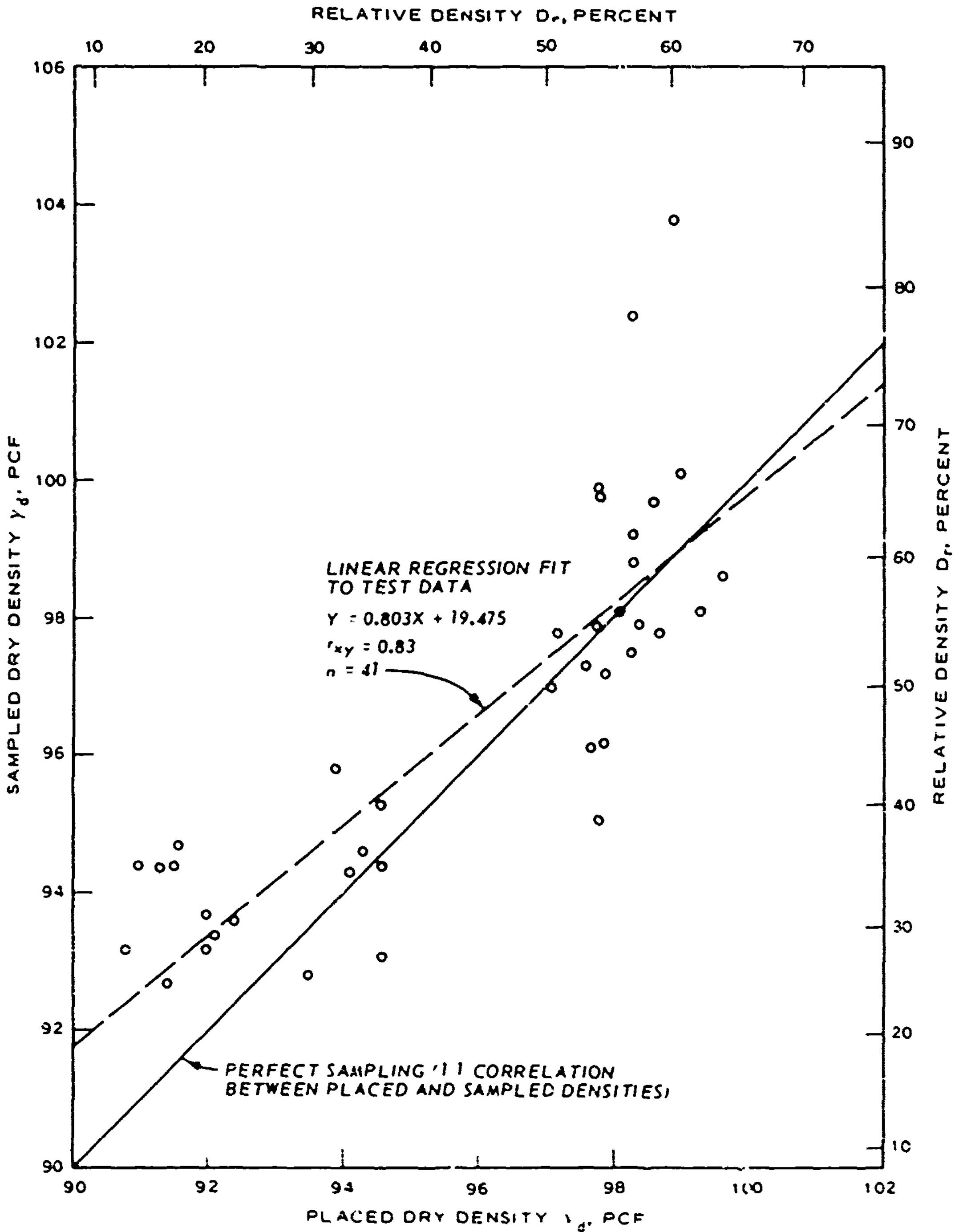


Figure 22. Comparison of as-placed and sampled densities from tests 5, 6, 7, 8, and 12

tests 5, 6, 7, 8, and 12 were used in Figure 22 because the placed density in tests 2 and 4 was determined from bulk rather than incremental box density measurements and did not provide the desired direct comparison. For reasons given previously, the data points at -6 and -10 pcf were not plotted in Figure 22. A linear regression analysis was performed on the data shown in Figure 22 and the linear fit derived is indicated by a dashed line in the plot. The equation of the line is:

$$y = 0.803x + 19.475$$

where

y = sampled density

x = placed density

The coefficient of correlation for the linear fit to the data is $r_{xy} = 0.83$ and the coefficient of determination is $(r_{xy})^2 = 0.69$. For a high level of confidence in fit, it is generally accepted that the coefficient of correlation should be 0.90 or more. On this basis, a coefficient of correlation of 0.83 may be termed indicative rather than definitive, so there is some level of uncertainty associated with the data trend shown in Figure 22. For comparison, a solid line was added to the figure to show the ideal correlation between placed and sampled density which could be achieved with perfect sampling (providing no other variables were influencing the results). The data trend in Figure 22 does indicate that sample densities tend to exceed placed densities at placed relative densities less than 60 percent, and that the reverse is true for placed densities more than 60 percent. This trend generally agrees well with the work of earlier investigators,[2] and has been ascribed to the mechanical effects of sampling, that is, sampling tends to slightly consolidate loose material and to loosen dense material. It should be noted that the data presented in Figures 21 and 22 are a comparison between as-placed and sampled density, and that other effects, such as the three variables previously mentioned, are not considered.

38. Two of the three variables previously discussed, the box

density measurement errors and the lateral density variations, are random in nature. Since these variations are random it is difficult to evaluate their effect on test results except in general terms. The third variable, density increases due to overburden pressure, is systematic and its effect on the comparison of placed and sampled densities can be assessed with reasonable accuracy from the data tabulated in Table 1. To this end, the corrected placed density data from Table 1 were used to construct Figures 23 and 24, which were plotted in the same way as Figures 21 and 22. Comparing Figures 21 and 23, it can be seen that the primary effect of the overburden corrections is to shift the mean deviation line in Figure 23 towards the vertical (zero) axis while the standard deviation remains relatively unchanged. This is consistent with the previous assumption of systematic variation. Comparing Figures 22 and 24, it can be seen that the linear regression fit to the data in Figure 24 is a line which is closer to the line of perfect sampling. Both regression fits exhibit a similar trend in slope; however, the linear fit in Figure 24 crosses the perfect sampling line at a relative density of about 36 percent. There is a pronounced scatter of data points in both plots, particularly for those points falling in the placed relative density range between 50 and 60 percent. The coefficients of correlation and determination for Figure 24 are 0.82 and 0.67, respectively, and these are nearly identical with similar values from the regression fit presented in Figure 22.

39. Since these data and earlier work[2] exhibit a generally similar trend, Figures 25-31 were prepared for further comparisons. In Figures 25-31, the density variation of sample increments from placed density at the same depth is plotted versus increment location in the sample tube. The abcissa of each plot is dry density; the ordinate is scaled as distance from the bottom of the sampling tube to the center of each density increment. The figures include information on sample depth within each specimen, sample identification number, and the overburden pressure at which the sample was taken. The upper plot in Figures 25-31 shows sampled density variations from as-placed density; the lower plot shows variations from placed density which has been

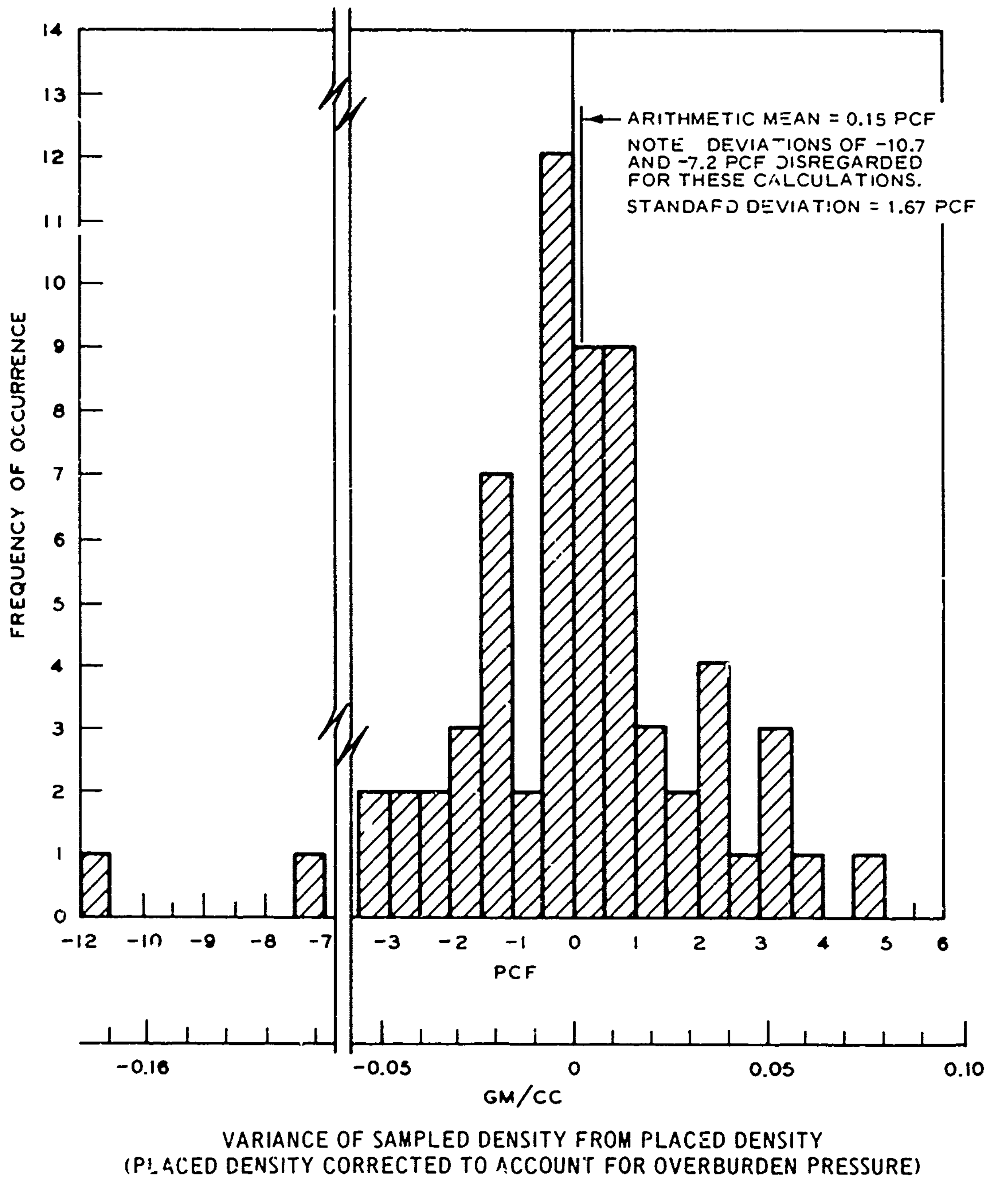


Figure 23. Distribution of corrected density variations

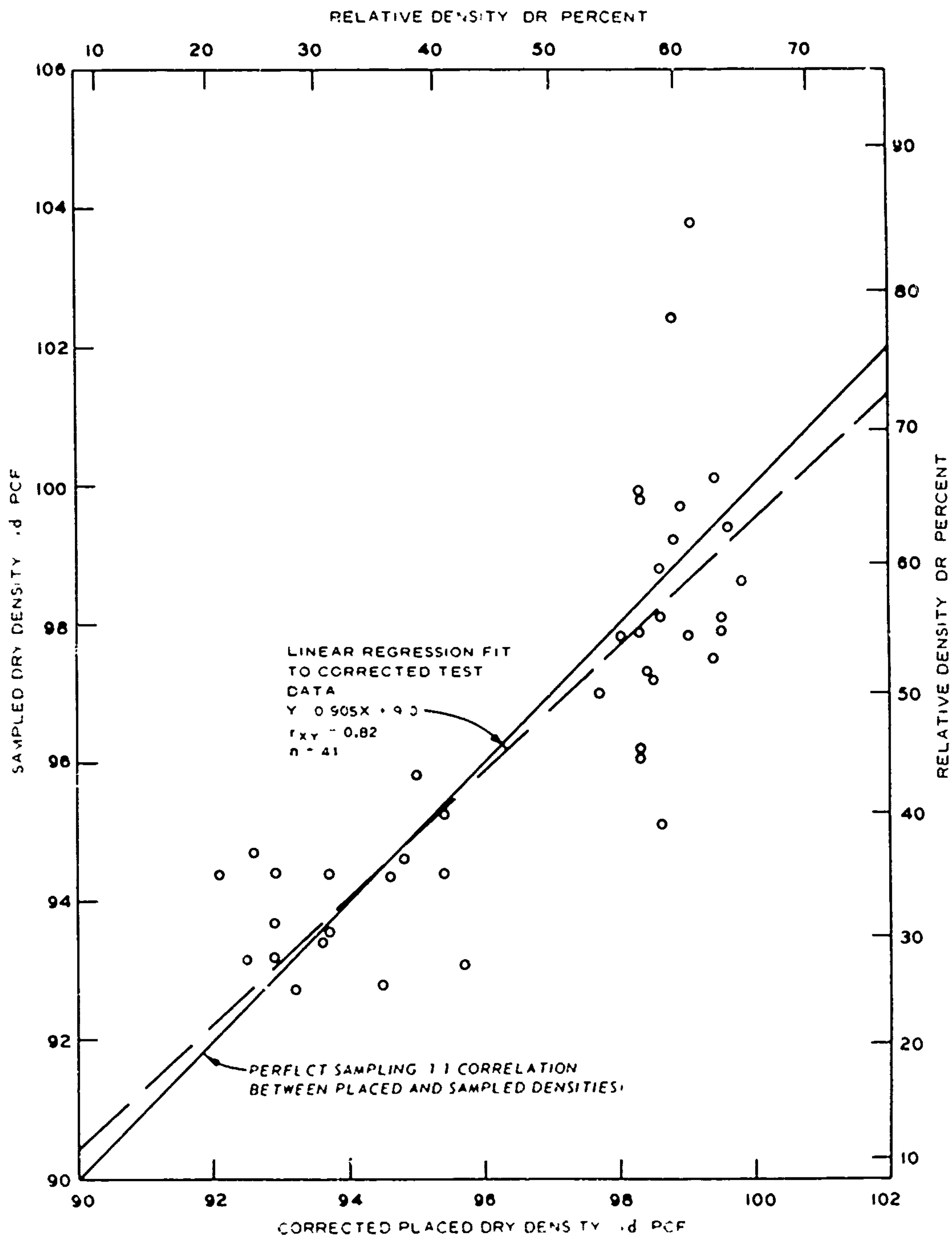
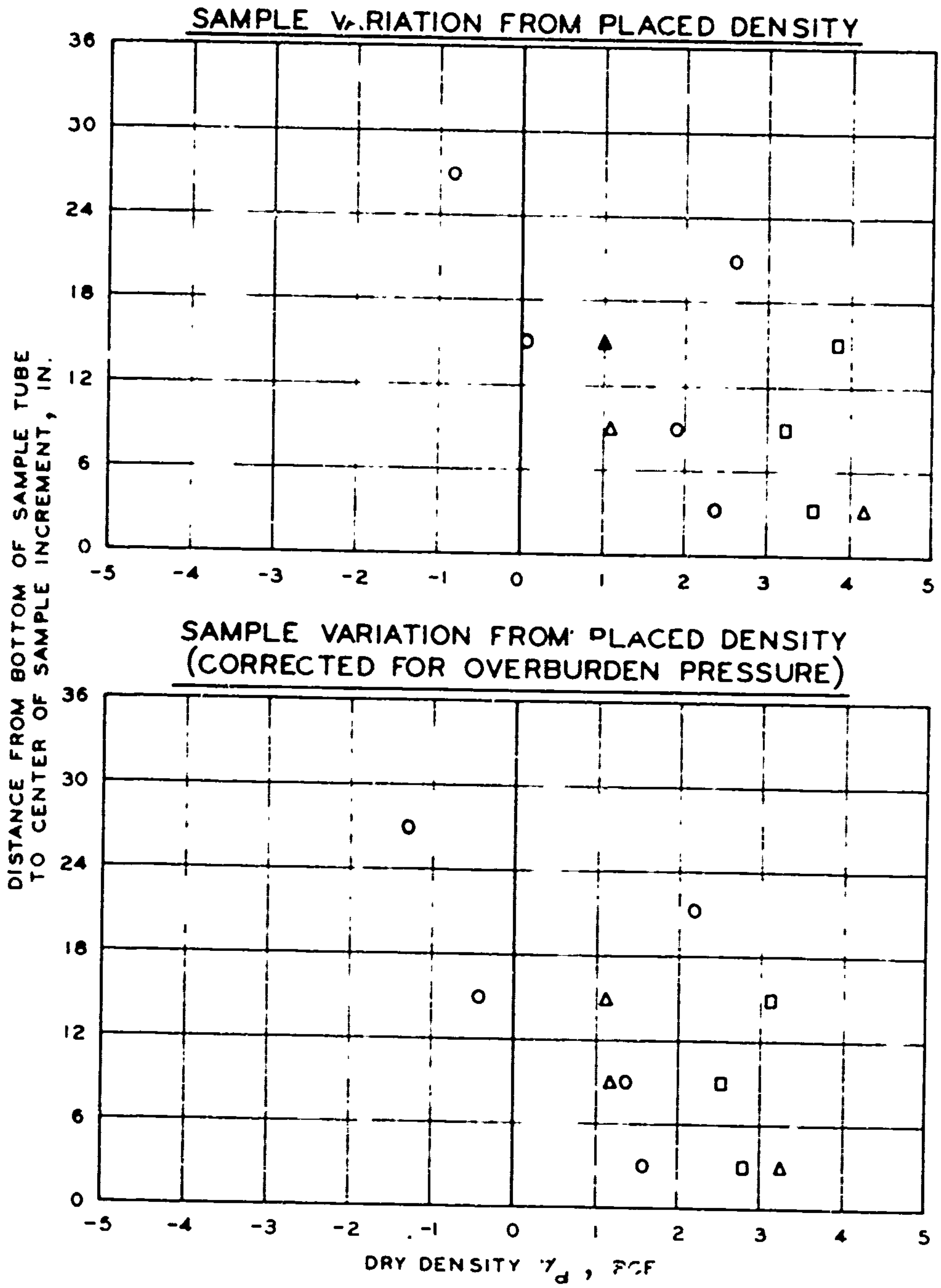


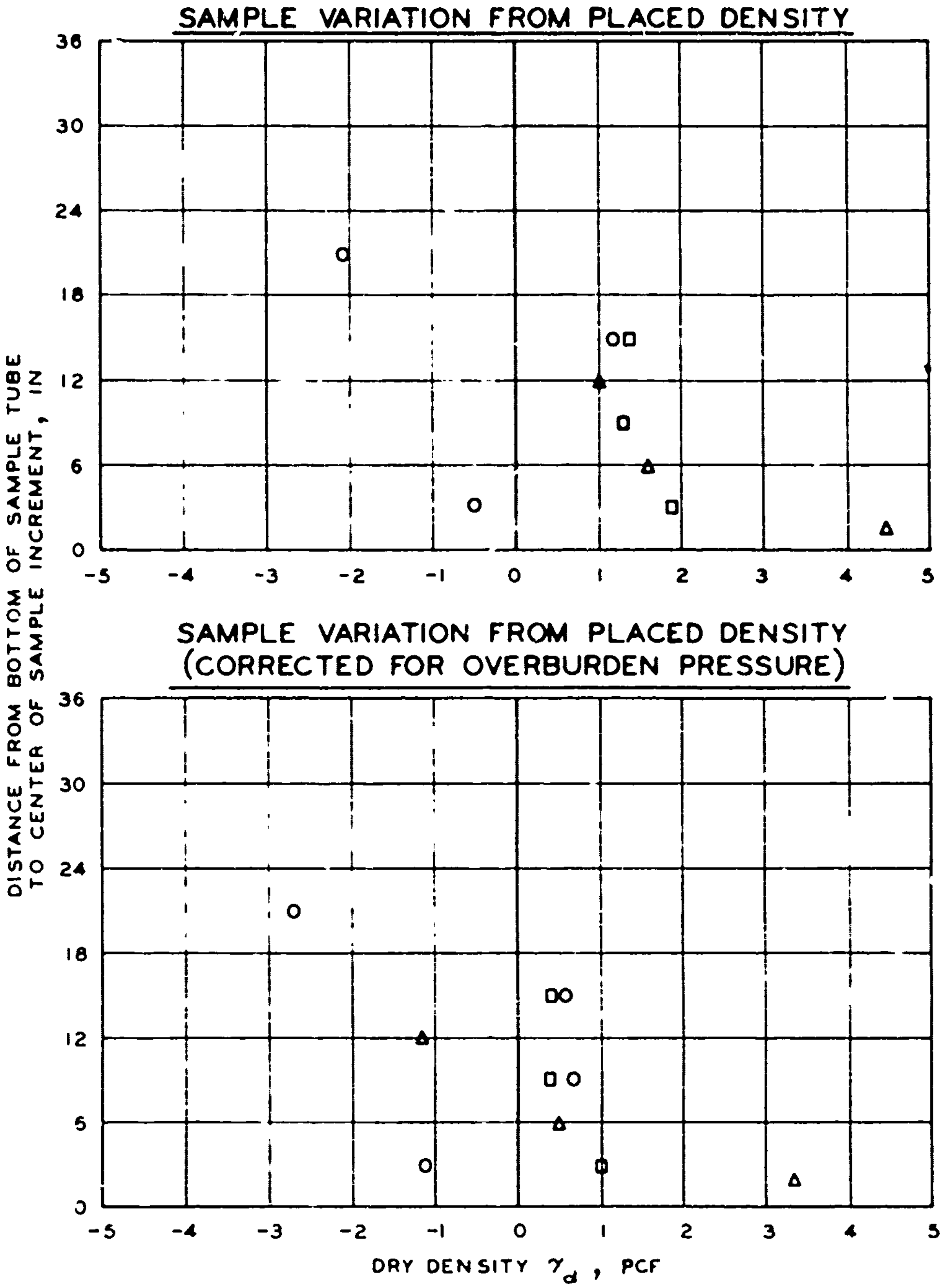
Figure 24. Comparison of placed density, corrected for overburden pressure applied, with sampled density from tests 5, 6, 7, 8, and 12



LEGEND

SYMBOL	SAMPLE NO	DEPTH IN SPECIMEN, IN	OVERBURDEN PRESSURE, PSI
O	1	0 - 27	10
□	2	30 - 48	40
Δ	3	48 - 65	80

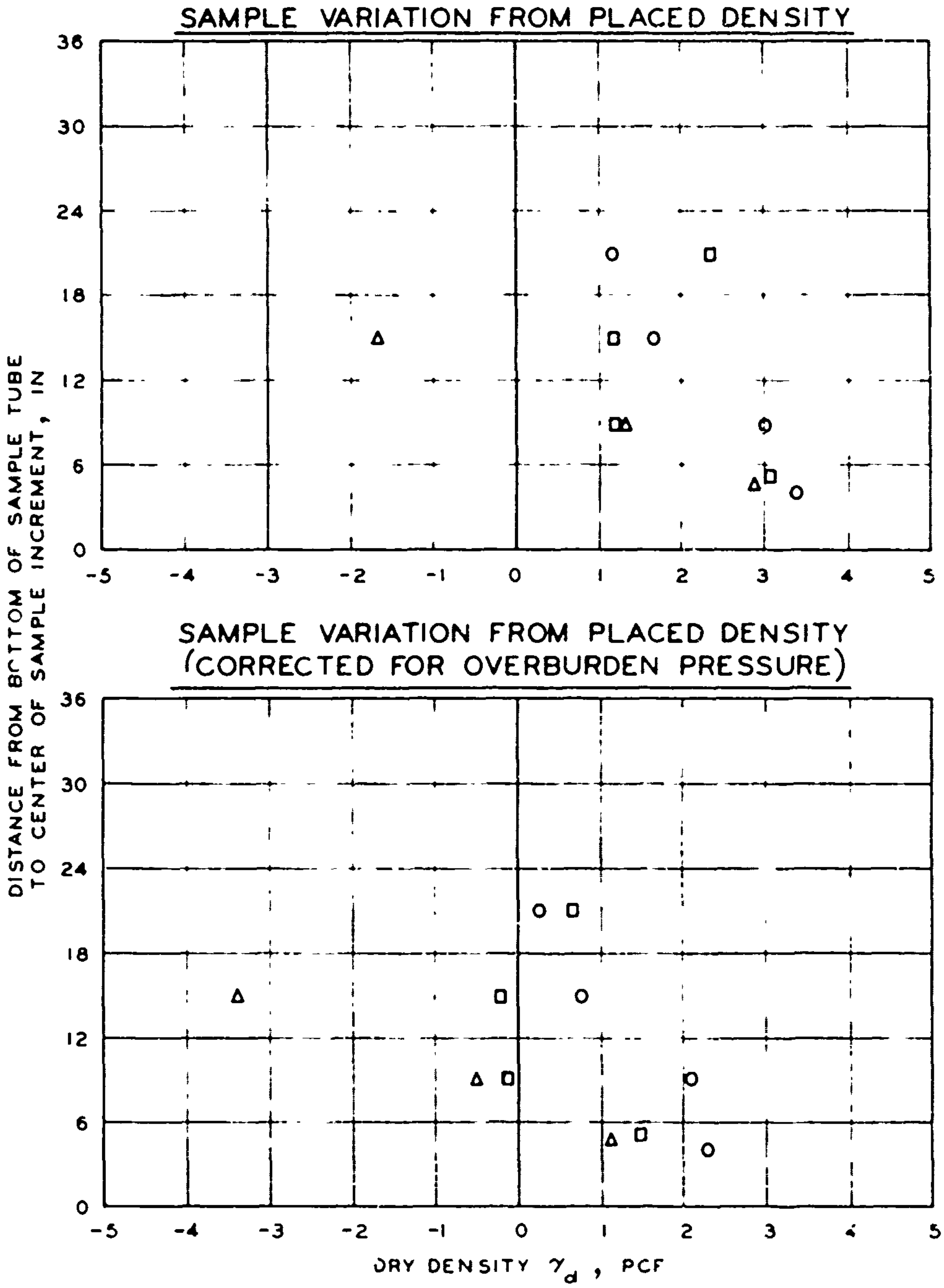
Figure 25. Density variation versus location in sample tube from specimen 2, D_r = 40 percent



LEGEND

SYMBOL	SAMPLE NO	DEPTH IN SPECIMEN, IN	OVERBURDEN PRESSURE, PSI
O	1	0-23	10
□	2	23-41	40
Δ	4	42-65	80

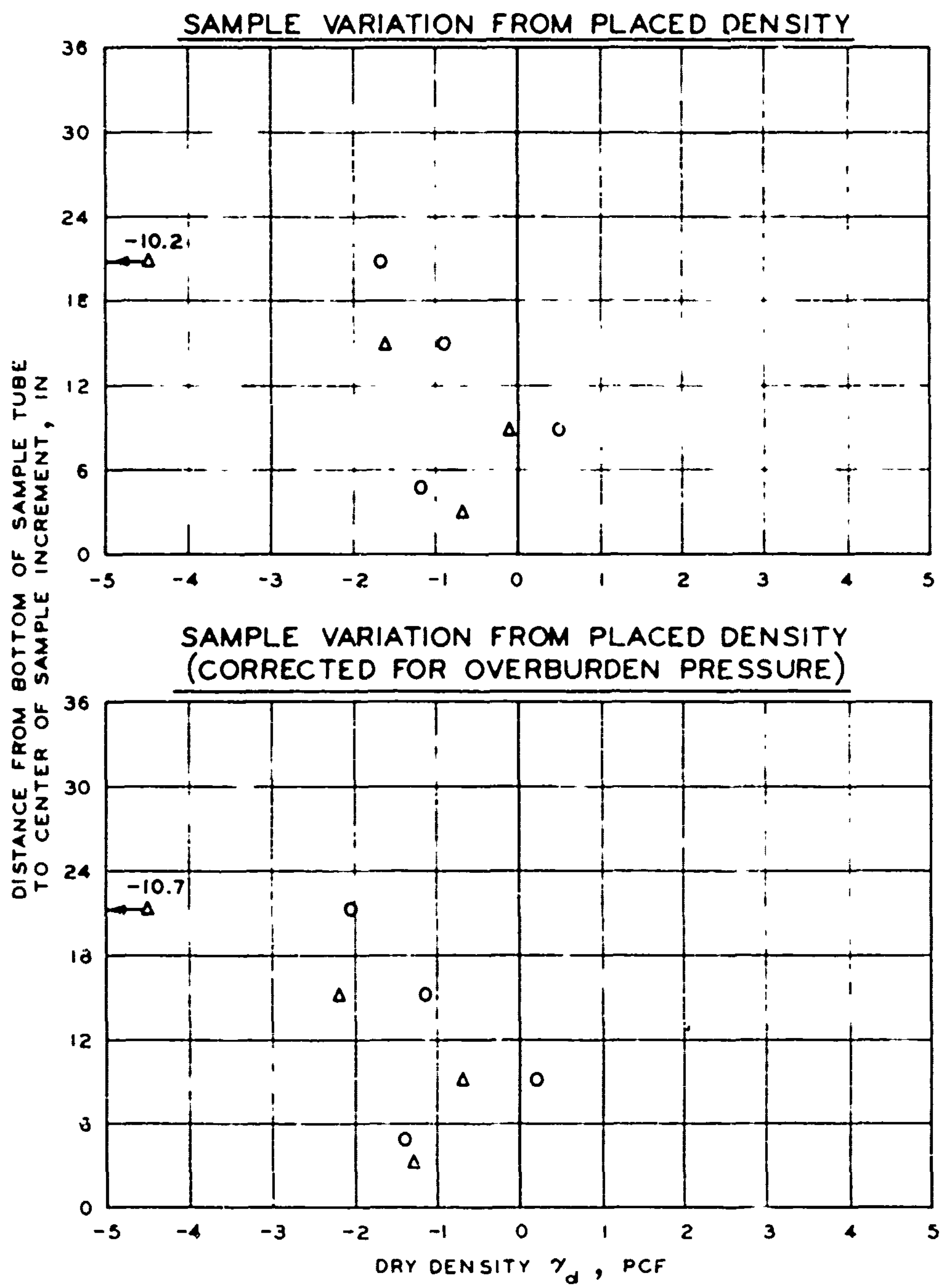
Figure 26. Density variation versus location in sample tube from specimen 4, D_r = 35 percent



LEGEND

SYMBOL	SAMPLE NO	DEPTH IN SPECIMEN, IN	OVERBURDEN PRESSURE, PSI
O	1	0 - 24	10
□	2	24 - 48	40
Δ	3	48 - 72	80

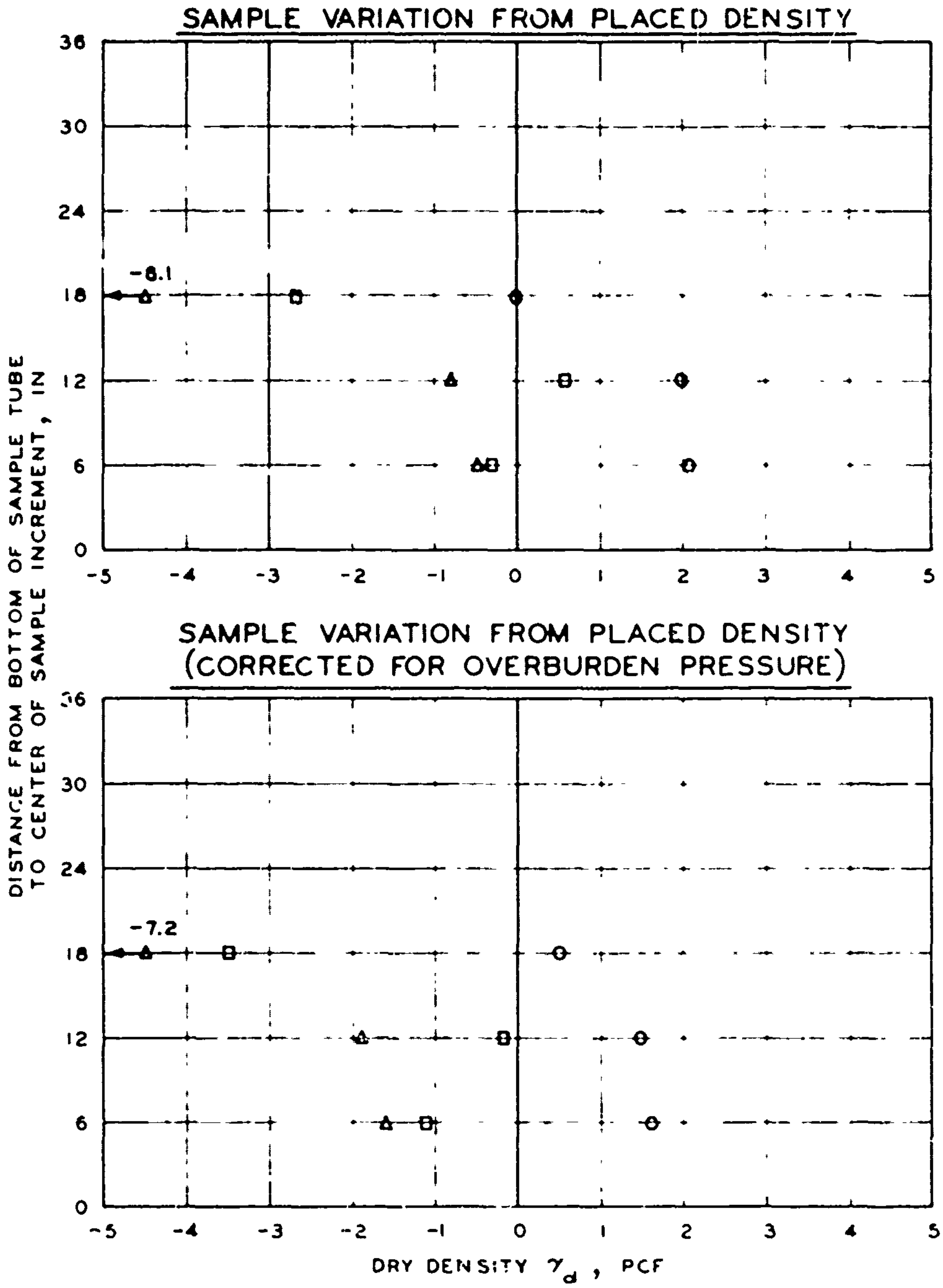
Figure 27. Density variation versus location in sample tube from specimen 5, D_r = 20 percent



LEGEND

SYMBOL	SAMPLE NO	DEPTH IN SPECIMEN IN.	OVERBURDEN PRESSURE, PSI
O	1	0-21	10
Δ	4	44-60	80

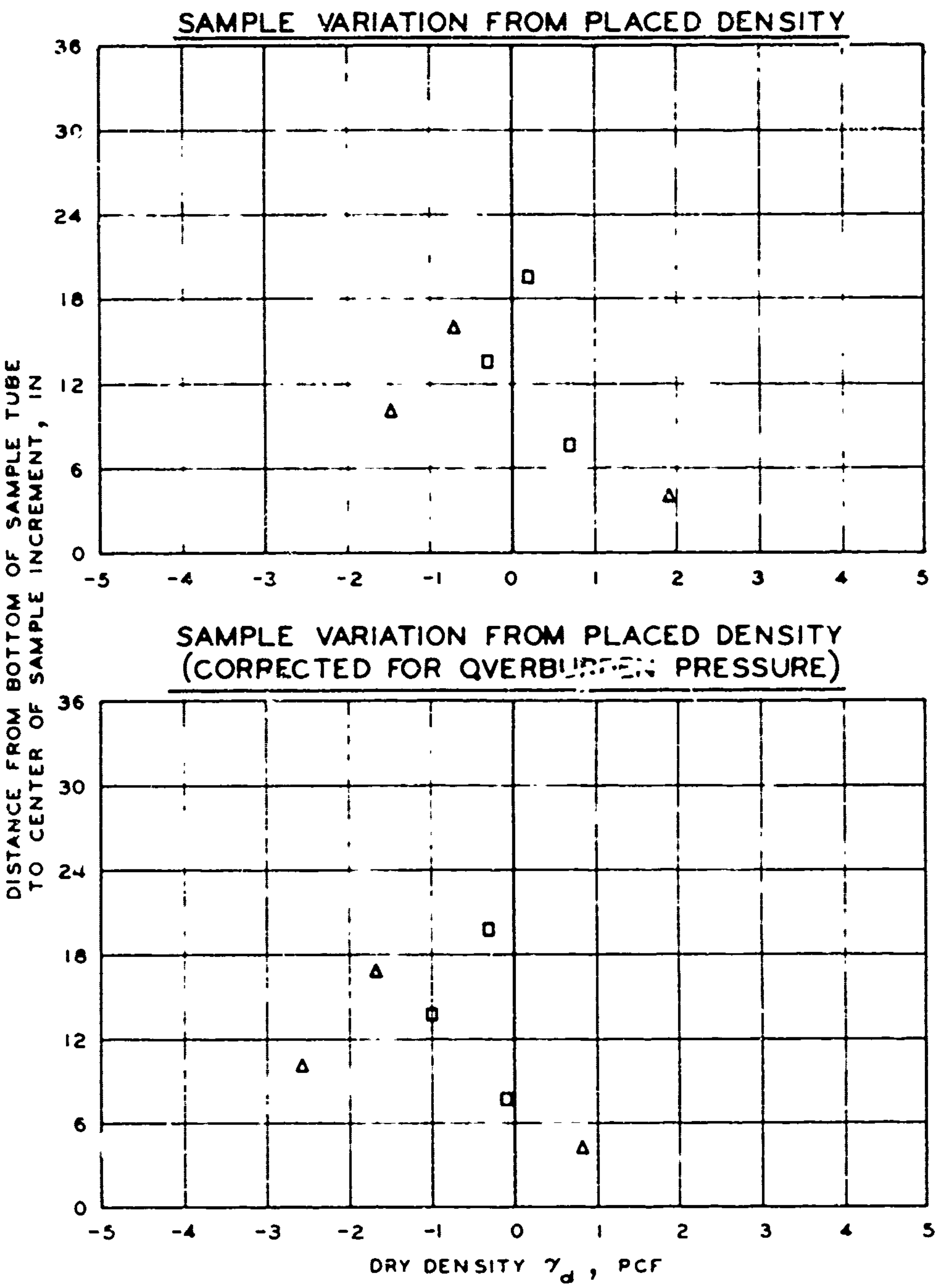
Figure 28. Density variation versus location in sample tube from specimen 6, D_r = 55 percent



LEGEND

SYMBOL	SAMPLE NO	DEPTH IN SPECIMEN, IN	OVERBURDEN PRESSURE, PSI
O	1	0 - 16	10
□	3	30 - 46	40
Δ	4	50 - 69	80

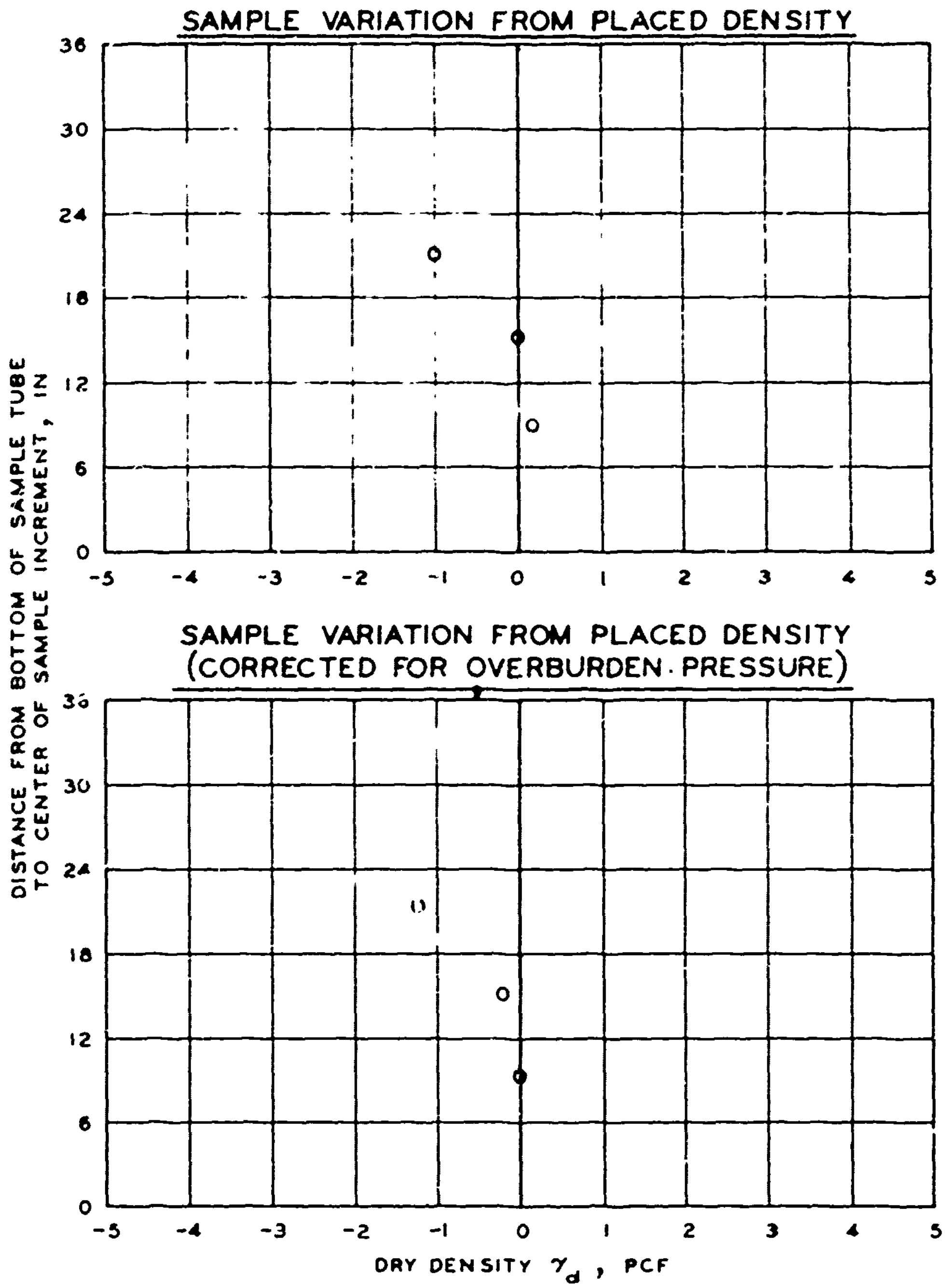
Figure 29. Density variation versus location in sample tube from specimen 7, D_r = 55 percent



LEGEND

SYMBOL	SAMPLE NO	DEPTH IN SPECIMEN, IN.	OVERBURDEN PRESSURE, PSI
□	2	21-39	40
Δ	3	47-67	80

Figure 30. Density variation versus location in sample tube from specimen 8, D_r = 35 percent



LEGEND

SYMBOL	SAMPLE NO	DEPTH IN SPECIMEN, IN.	OVERBURDEN PRESSURE, PSI
O	1	0-18	10

Figure 31. Density variation versus location in sample tube from specimen 12, D_r = 60 percent

corrected to account for the overburden pressure applied. While Figures 25-31 exhibit considerable scatter, the general trend of the data obtained at relative densities ranging from 20 to 60 percent indicates that sampled density decreases with increasing distance from the bottom of the sample tube. This trend is similar to results obtained in the earlier work on a similar sand placed at $D_r \approx 90$ percent; however, in the earlier study results at $D_r \approx 20$ percent showed a reverse condition.[2] Also, density corrections based on location in the sampler tube derived in the previous study are not consistent with results of this investigation at intermediate relative densities, i.e., D_r from 30 to 60 percent. The same sampling procedures were used in both studies, so the difference in results may be attributed to test conditions (solid wall versus stacked ring containers) or to the effect of the variables cited earlier.

40. The preceding analysis illustrates the difficulty experienced in separating test variables from an assessment of sampling accuracy. In this instance, the corrections for density changes due to overburden pressure are apparently very significant to the test results. The random variables associated with placed density determinations are much less susceptible to evaluation and cause some degree of uncertainty in an assessment of sampling accuracy. However, an assessment can be made from Figures 21 and 23; by definition, 95 percent of the sampling data must fall within the range of ±2 pcf. Within this range, sampling accuracy is indicated to be ±3.4 pcf for density samples taken at relative densities D_r ranging from 20 to 60 percent. The linear regression data fits presented in Figures 22 and 24 indicate that sampling slightly densifies the sand at low relative densities ($D_r < 40$ percent) and tends to loosen denser ($D_r > 50$ percent) sand.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

41. In the analysis section of this report, considerable attention was given to the test variables which can influence test results, and it was noted that placed density at the time of sampling probably varied from +2.9 to -1.5 pcf from measured values due to the combined effects of the test variables.

42. The sampled versus placed density comparisons presented suggest that sampling accuracy using the techniques described is within ±3.4 pcf for 95 percent of the sampling conducted at relative densities D_r ranging from 20 to 60 percent. However, it can also be concluded that a more meaningful assessment of sampling accuracy could have been made had it been possible to exercise better placed density control during the study; it is very probable that in this event the apparent accuracy of sampling would have shown a corresponding improvement.

43. Despite the uncertainties cited, results of this and earlier work exhibit generally similar trends. For instance, this and the preceding work indicate that sampling tends to slightly densify loose sand (D_r < 40 percent) and tends to slightly loosen denser sand (D_r > 50 percent). The plots presenting linear regression fits to selected test data also lead to the conclusion that overburden pressure corrections can significantly influence the results of density determinations made with the sampling techniques described. More definitive conclusions regarding sampling accuracy cannot be advanced because of the uncertainty associated with the placed density results obtained in this study.

Recommendations

44. The undisturbed sampling phase of the current study should be extended with the following revisions to test procedures:

<u>a</u>. An improved sand raining technique should be employed

so that density variations across the specimen can be reduced to the practical minimum (preferably ±0.5 pcf or less).

b. A system to measure vertical deformation of the specimen should be added to the test apparatus.

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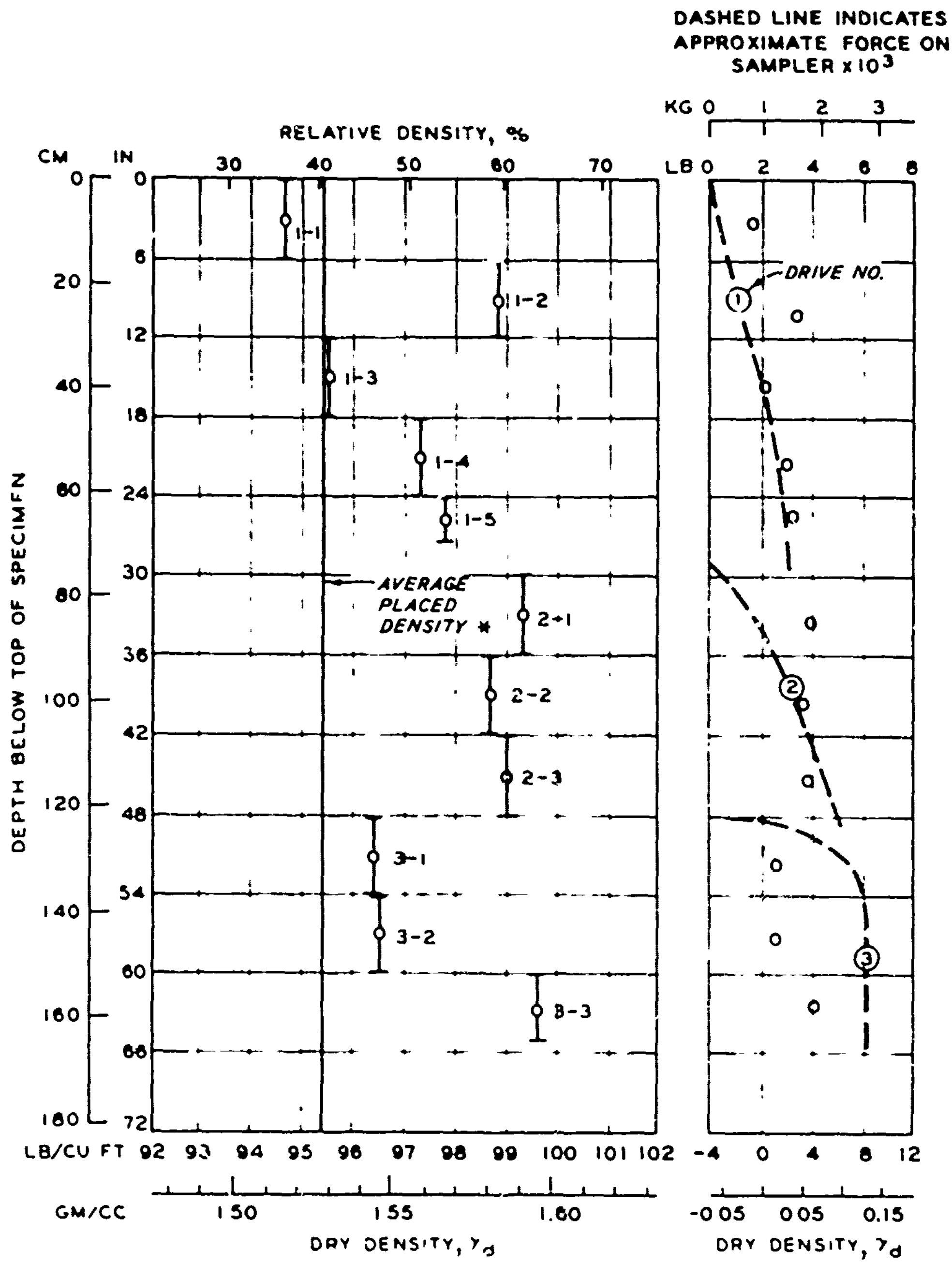
Table 1

Summary of Placed and Sampled Density Data

Test No.	Nominal D_r, Percent	Depth Inches	As Placed Dry Density γ_d, pcf	Overburden Density Correction From Fig. 18 pcf	Corrected Placed Dry Density γ_d, pcf	Sample No.	Sampled Dry Density γ_d, pcf	Sample Variation From Placed Dry Density pcf	Sample Variation From Corrected Placed Dry Density pcf
2	40	6	95.4	0.5	95.9	1-1	94.6	-0.8	-1.3
		12	(From	0.5	95.9	1-2	98.1	2.7	2.2
		18	Bulk	0.5	95.9	1-3	95.5	0.1	-0.4
		24	Measurement)	0.5	95.9	1-4	97.3	1.9	1.4
		30		0.8	96.2	1-5	97.8	2.4	1.6
		36		0.8	96.2	2-1	99.3	3.9	3.1
		42		0.8	96.2	2-2	98.7	3.3	2.5
		48		0.8	96.2	2-3	99.0	3.6	2.8
		54		0.9	96.3	3-1	96.4	1.0	0.1
		60		0.9	96.3	3-2	96.5	1.1	0.2
		66		0.9	96.3	3-3	99.6	4.2	3.3
		72		0.9	96.3	--	--	--	--
4	35	6	94.4	0.6	95.0	1-1	92.3	-2.1	-2.7
		12	(From	0.6	95.0	1-2	95.6	1.2	0.6
		18	Bulk	0.6	95.0	1-3	95.7	1.3	0.7
		24	Measurement)	0.6	95.0	1-4	93.9	-0.5	-1.1
		30		1.0	95.4	2-1	95.8	1.4	0.4
		36		1.0	95.4	2-2	95.7	1.3	0.3
		42		1.0	95.4	2-3	96.3	1.9	0.9
		48		1.1	95.5	3-1	95.7	1.3	0.2
		54		1.1	95.5	4-1	95.4	1.0	-0.1
		60		1.1	95.5	4-2	96.0	1.6	0.5
		66		1.1	95.5	4-3	98.9	4.5	3.6
		72		--	--	--	--	--	--
5	20	6	92.0	0.9	92.9	1-1	93.2	1.2	0.3
		12	92.0	0.9	92.9	1-2	93.7	1.7	0.8
		18	91.6	1.0	92.6	1-3	94.7	3.1	2.1
		24	91.0	1.1	92.1	1-4	94.4	3.4	2.3
		30	90.8	1.7	92.5	2-1	93.2	2.4	0.7
		36	92.2	1.4	93.6	2-2	93.4	1.2	-0.2
		42	92.4	1.3	93.7	2-3	93.6	1.2	-0.1
		48	91.3	1.6	92.9	2-4	94.4	3.1	1.5
		54	91.8	1.7	93.5	3-1	90.1	-1.7	-3.4
		60	91.4	1.8	93.2	3-2	92.7	1.3	-0.5
		66	91.5	1.8	93.3	3-3	94.4	2.9	1.1
		72	91.[illegible]	1.8	93.1	--	--	--	--
6	55	6	97.9	0.4	98.3	1-1	96.2	-1.7	-2.1
		12	98.7	0.3	99.0	1-2	97.8	-0.9	-1.2
		18	98.3	0.3	98.6	1-3	98.8	0.5	0.2
		24	99.3	0.2	99.5	1-4	98.1	-1.2	-1.4
		30	99.0	0.4	99.4	2-1	100.1	1.1	0.7
		36	98.3	0.5	98.8	2-2	102.4	4.1	3.6
		42	98.3	0.5	98.8	3-1	99.2	0.9	0.4
		48	98.1	0.5	98.6	4-1	87.9	-10.2	-10.7
		54	97.7	0.6	98.3	4-2	96.1	-1.6	-2.2
		60	97.1	0.6	97.7	4-3	97.0	-0.1	-0.7
		66	97.9	0.6	98.5	4-4	97.2	-0.7	-1.3
		72	98.3	0.6	98.9	--	--	--	--
7	55	6	98.1	0.5	98.6	1-1	98.1	0.0	0.5
		12	97.8	0.5	98.3	1-2	99.8	2.0	1.5
		18	97.8	0.5	98.3	1-3	99.9	2.1	1.6
		24	97.8	0.5	98.3	2-1	97.9	0.1	-0.4
		30	97.4	0.8	98.2	--	--	--	--
		36	97.8	0.8	98.6	3-1	95.1	-2.7	-3.5
		42	97.2	0.8	98.0	3-2	97.8	0.6	-0.2
		48	97.6	0.8	98.4	3-3	97.3	-0.3	-1.1
		54	98.2	1.1	99.3	4-1	92.1	-6.1	-7.2
		60	98.3	1.1	99.4	4-2	97.5	-0.8	-1.9
		66	98.4	1.1	99.5	4-3	97.9	-0.5	-1.6
		72	97.4	1.1	98.5	--	--	--	--
8	35	6	--	--	--	--	--	--	--
		12	94.3	0.5	94.8	1-2	94.6	0.3	-0.2
		18	--	--	--	--	--	--	--
		24	94.1	0.5	94.6	2-1	94.3	0.2	-0.3
		30	--	--	--	--	--	--	--
		36	94.6	0.8	95.4	2-2	94.4	-0.2	-1.0
		42	--	--	--	2-3	95.3	--	--
		48	95.4	0.8	96.2	--	--	--	--
		54	93.5	1.0	94.5	3-1	92.8	-0.7	-1.7
		60	94.6	1.1	95.7	3-2	93.1	-1.5	-2.6
		66	93.9	1.1	95.0	3-3	95.8	1.9	0.8
		72	95.6	1.1	96.7	--	--	--	--
12	60	6	99.6	0.2	99.8	1-1	98.6	-1.0	-1.2
		12	99.4	0.2	99.6	1-2	99.4	0.0	-0.2
		18	--	--	--	--	--	--	--
		24	99.8	0.2	100.0	--	100.0	0.2	0.0
		30	--	--	--	--	--	--	--
		36	98.9	0.2	99.1	2-2	103.8	4.9	4.7
		42	--	--	--	--	--	--	--
		48	98.9	0.3	99.2	--	--	--	--
		54	--	--	--	--	--	--	--
		60	98.6	0.3	98.9	3-2	99.7	1.1	0.8
		66	99.6	0.3	99.9	--	--	--	--
		72	98.5	0.3	98.8	--	--	--	--



PLACEMENT DENSITY AND DENSITY OF SAMPLED INCREMENTS VS DEPTH

VARIATION FROM PLACED DENSITY

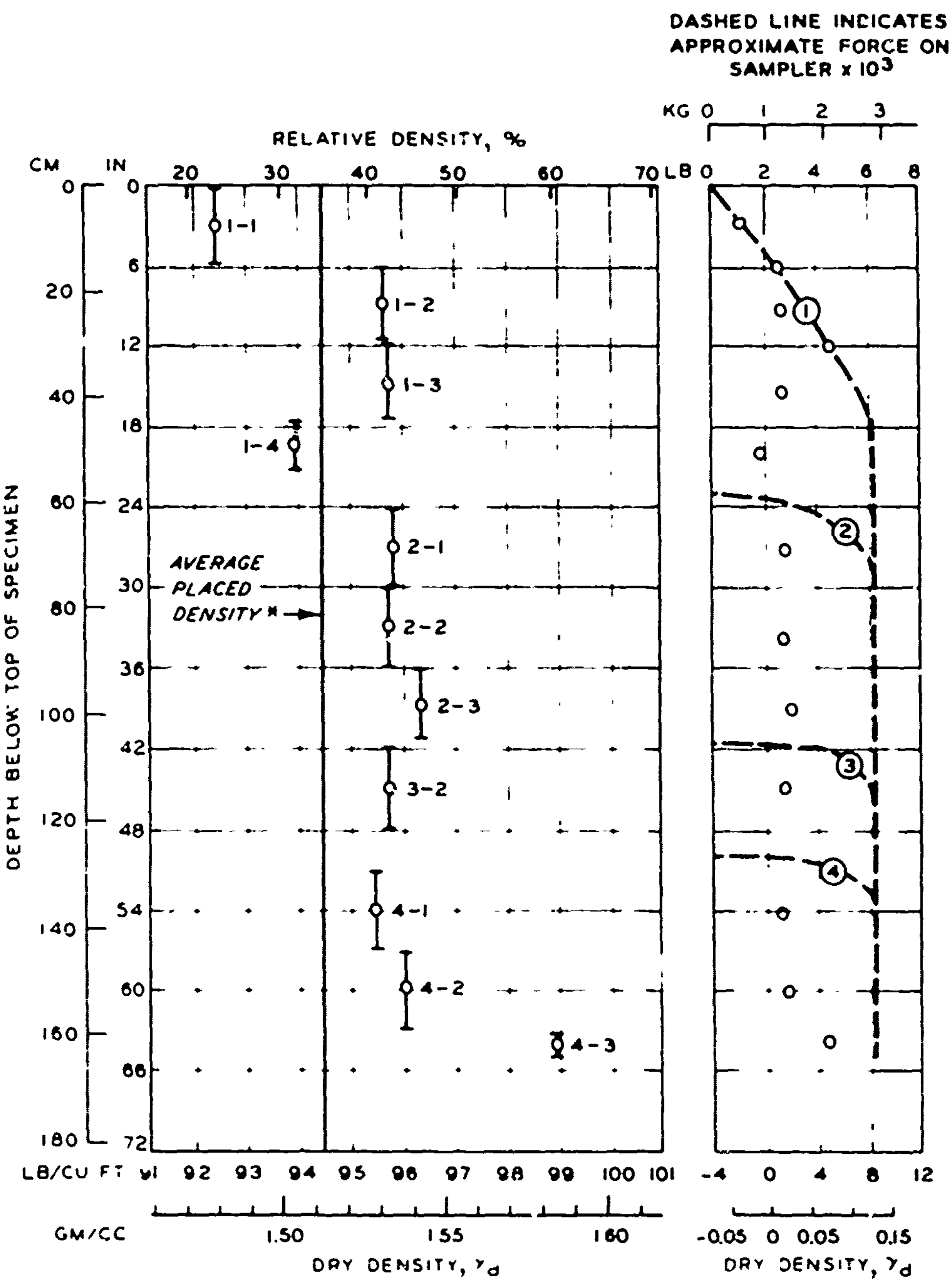
* COMPUTED FROM TOTAL WEIGHT AND VOLUME OF SPECIMEN

LEGEND

- I PLACED DENSITY
- Φ SAMPLED DENSITY
- 1-3 FIRST SAMPLE-THIRD SAMPLE INCREMENT

DENSITY TEST RESULTS
REID BEDFORD SAND

NOMINAL RELATIVE DENSITY, $D_r = 40\%$
(SPECIMEN 2)



PLACEMENT DENSITY AND DENSITY OF SAMPLED INCREMENTS VS DEPTH

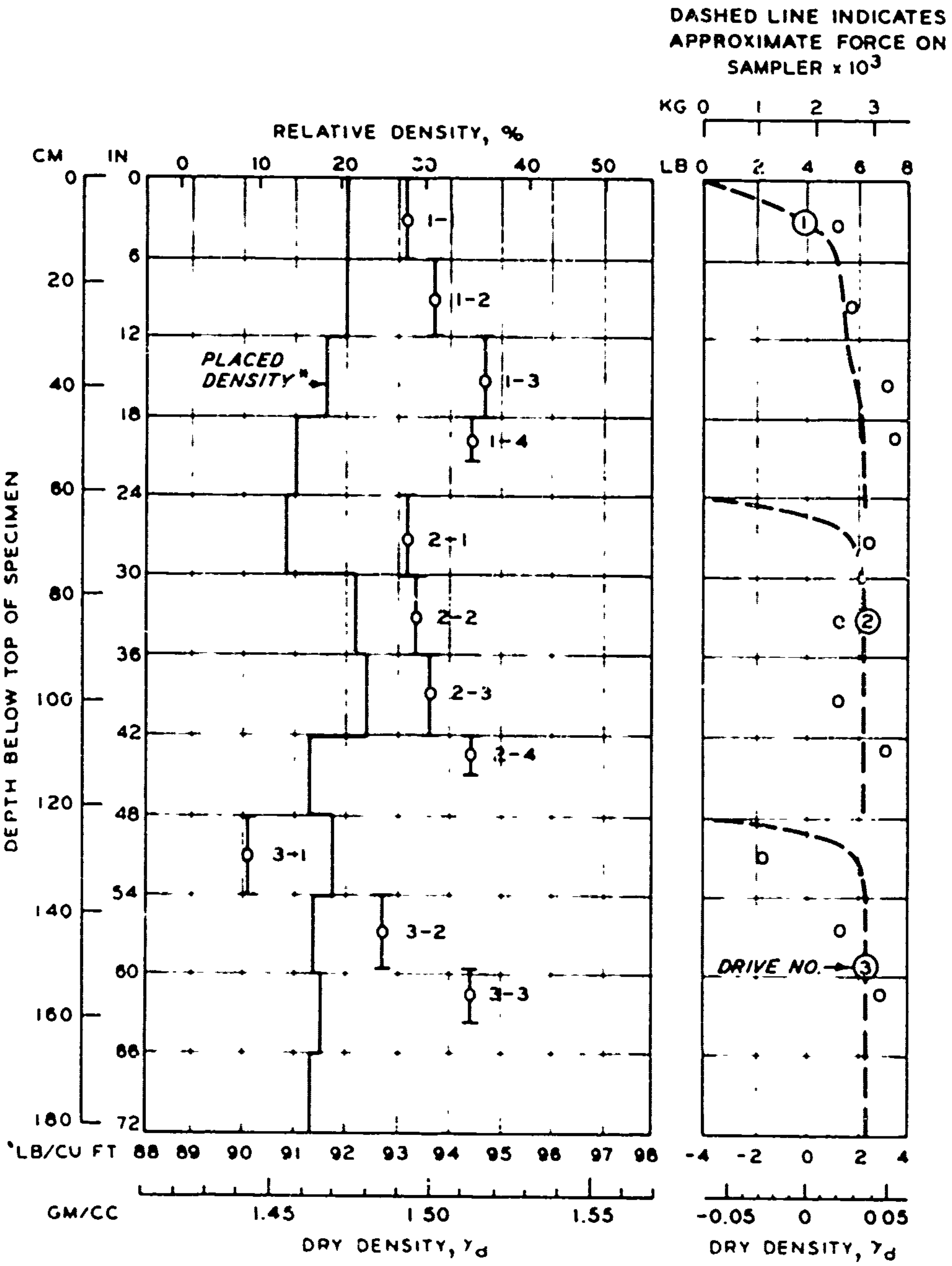
VARIATION FROM PLACED DENSITY

* COMPUTED FROM TOTAL WEIGHT AND VOLUME OF SPECIMEN

LEGEND

- I PLACED DENSITY
- ɸ SAMPLED DENSITY
- 1-3 FIRST SAMPLE-THIRD SAMPLE INCREMENT

DENSITY TEST RESULTS
REID BEDFORD SAND
NOMINAL RELATIVE DENSITY, $D_r = 35\ \%$
(SPECIMEN 4)



PLACEMENT DENSITY AND DENSITY OF SAMPLED INCREMENTS VS DEPTH

VARIATION FROM PLACED DENSITY

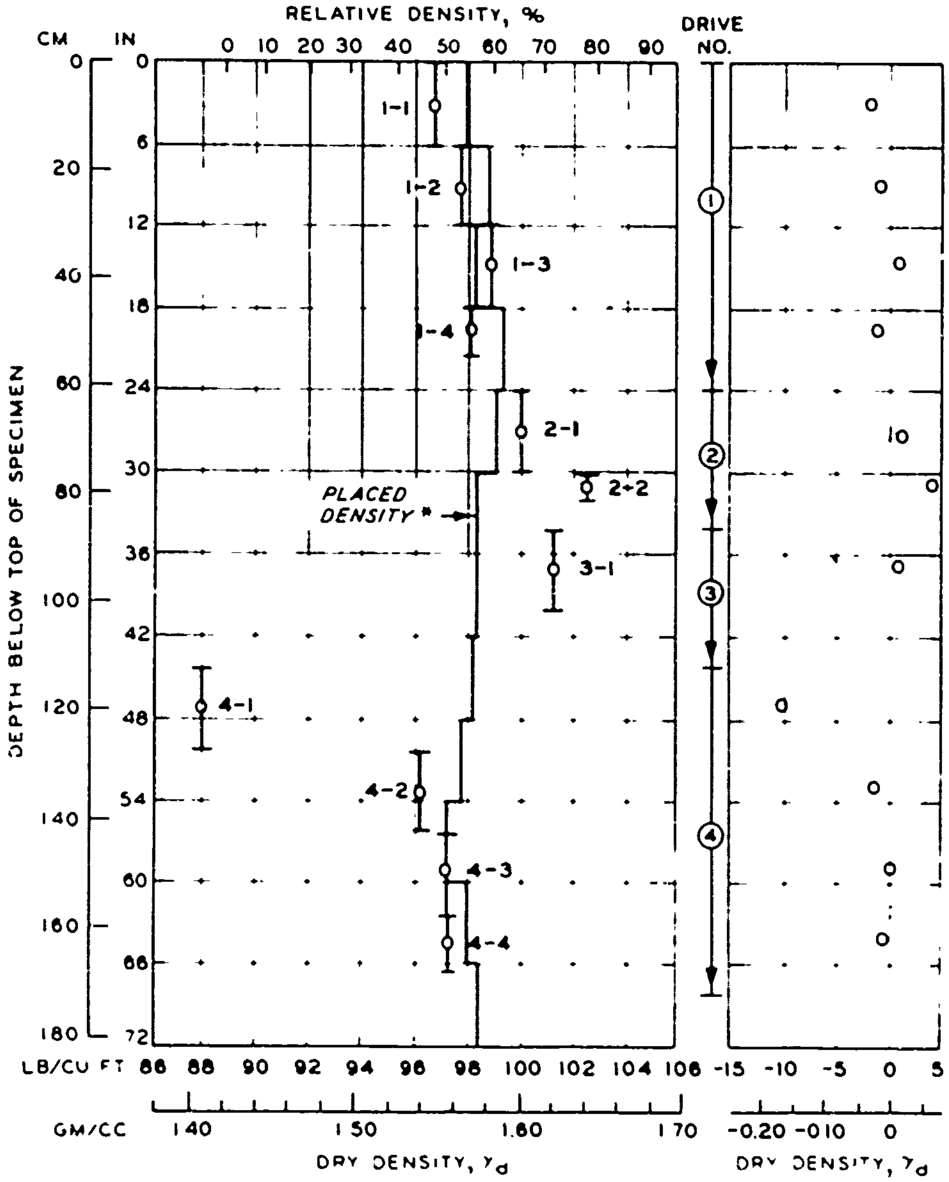
* FROM BOX DENSITY MEASUREMENTS

LEGEND

I PLACED DENSITY
Φ SAMPLED DENSITY
1-3 FIRST SAMPLE-THIRD SAMPLE INCREMENT

DENSITY TEST RESULTS
REID BEDFORD SAND

NOMINAL RELATIVE DENSITY, D_r = 20%
(SPECIMEN 5)



PLACEMENT DENSITY AND DENSITY OF SAMPLED INCREMENTS VS DEPTH

VARIATION FROM PLACED DENSITY

* FROM BOX DENSITY MEASUREMENTS

LEGEND

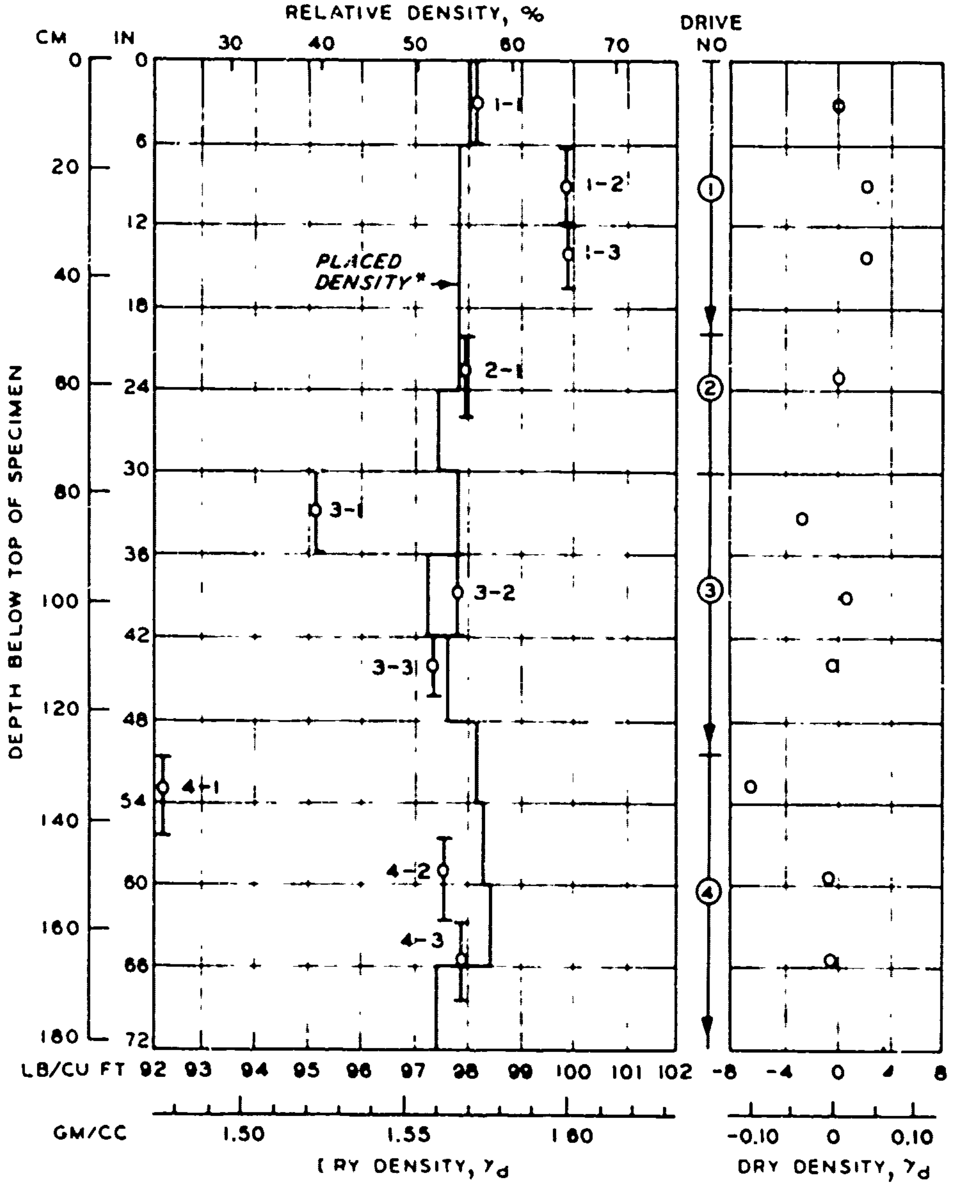
I PLACED DENSITY

Φ SAMPLED DENSITY

1-3 FIRST SAMPLE-THIRD SAMPLE INCREMENT

DENSITY TEST RESULTS
REID BEDFORD SAND

NOMINAL RELATIVE DENSITY, D_r = 55%
(SPECIMEN 6)



PLACEMENT DENSITY AND DENSITY OF SAMPLED INCREMENTS VS DEPTH

VARIATION FROM PLACED DENSITY

* FROM BOX DENSITY MEASUREMENTS

LEGEND

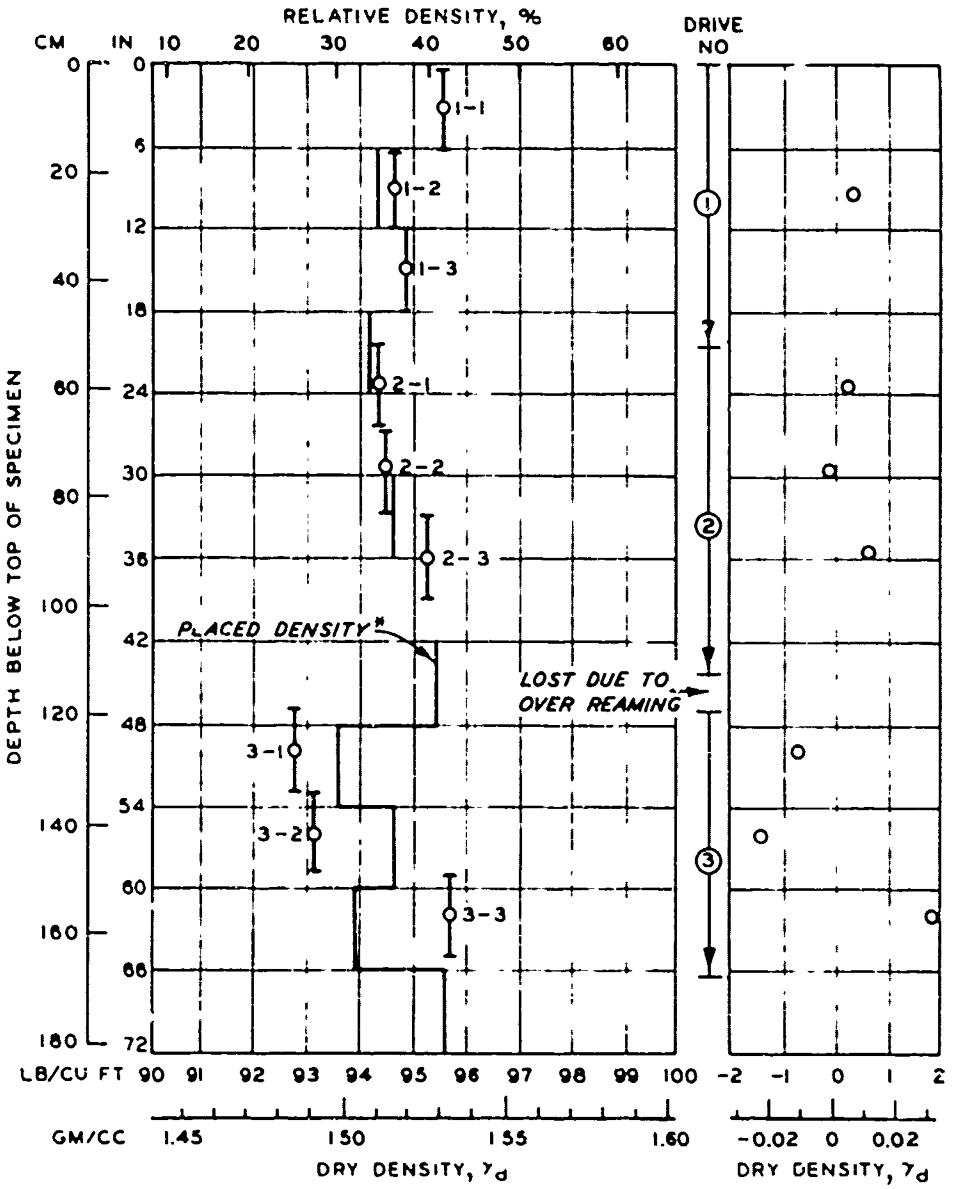
I PLACED DENSITY

ϕ SAMPLED DENSITY

1-3 FIRST SAMPLE-THIRD SAMPLE INCREMENT

DENSITY TEST RESULTS
REID BEDFORD SAND

NOMINAL RELATIVE DENSITY, D_r = 55%
(SPECIMEN 7)



PLACEMENT DENSITY AND DENSITY OF SAMPLED INCREMENTS VS DEPTH

VARIATION FROM PLACED DENSITY

* FROM BOX DENSITY MEASUREMENTS

LEGEND

I PLACED DENSITY

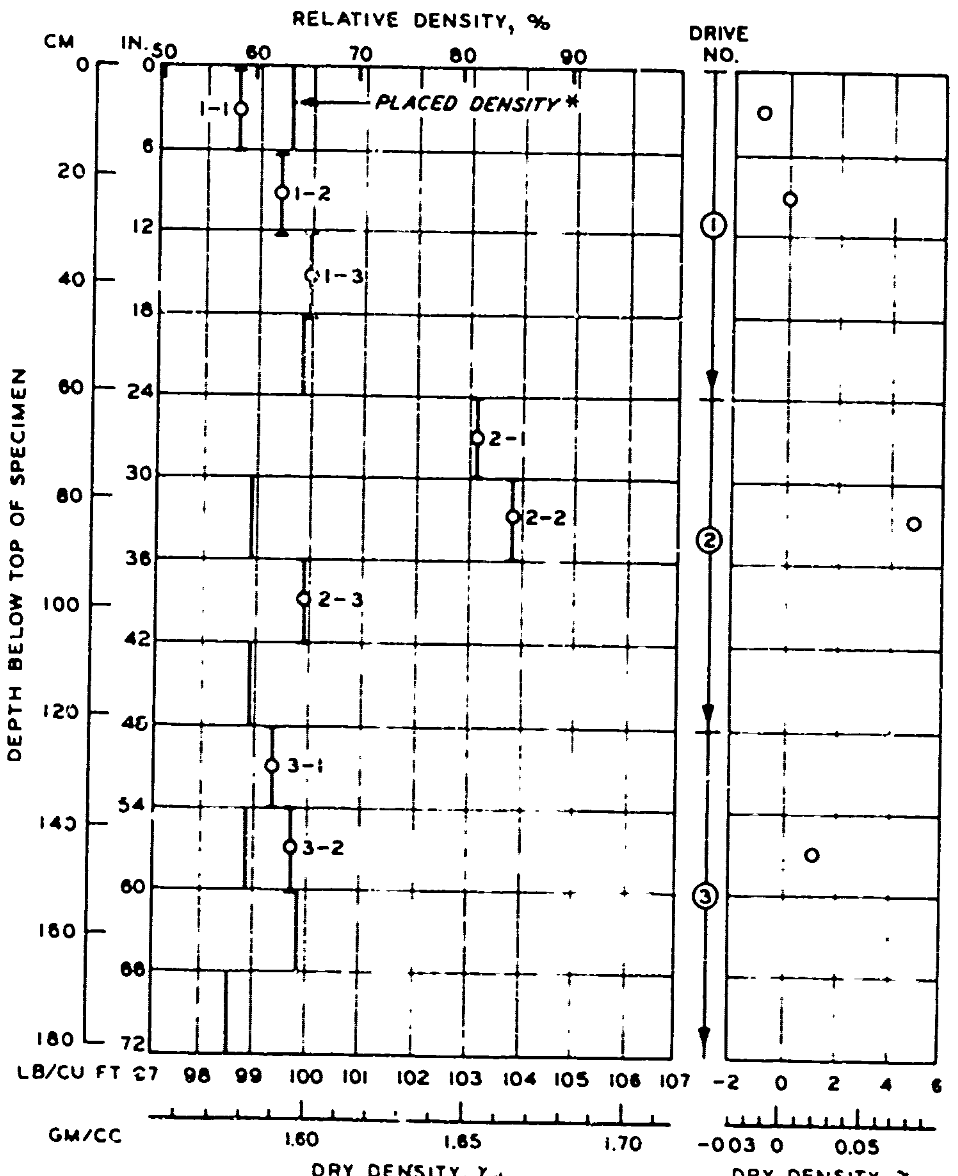
Φ SAMPLED DENSITY

1-3 FIRST SAMPLE-THIRD SAMPLE INCREMENT

DENSITY TEST RESULTS
REID BEDFORD SAND

NOMINAL RELATIVE DENSITY, $D_r = 35\%$

(SPECIMEN 8)



PLACEMENT DENSITY AND DENSITY OF SAMPLED INCREMENTS VS DEPTH

VARIATION FROM PLACED DENSITY

* FROM BOX DENSITY MEASUREMENTS

LEGEND

I PLACED DENSITY

Φ SAMPLED DENSITY

1-3 FIRST SAMPLE-THIRD SAMPLE INCREMENT

DENSITY TEST RESULTS REID BEDFORD SAND

NOMINAL RELATIVE DENSITY, $D_r = 60\%$

(SPECIMEN 12)

APPENDIX A

PETROGRAPHIC EXAMINATION OF
REID-BEDFORD MODEL SAND

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION. CORPS OF ENGINEERS
P O BOX 631
VICKSBURG. MISSISSIPPI 39180

IN REPLY REFER TO WESSG

23 April 1974

MEMORANDUM FOR: Dr. W. F. Marcuson

SUBJECT: Petrographic Examination of the Reid-Bedford Model Sand

General

1. A sample of the Reid-Bedford model sand was analyzed by petrographic and statistical techniques for the purpose of determining gross mineralogy, degree of grain roundness, and the basic statistical parameters exhibited by this sediment.

Size-distribution statistics

2. Grain-size data obtained from the gradation curve were recalculated in phi (Ø)* units and plotted on probability paper. The resulting curve permitted the mean and median grain size, standard deviation, skewness, and the kurtosis to be calculated. These parameters are summarized below.

a. Mean grain size: 2.00 Ø = 0.25 mm. This corresponds to the division between medium and fine sand.**

b. Median grain size: 2.00 Ø = 0.25 mm.

c. Standard deviation: 0.50 Ø = 0.71 mm. The following classification is used here:

Very well sorted: $<$ 0.35 Ø.
Well sorted: 0.35-0.50 Ø.
Moderately well sorted: 0.50-0.71 Ø.
Moderately sorted: 0.71-1.00 Ø.
Poorly sorted: 1.00-2.00 Ø.

Thus the Reid-Bedford sand is well to moderately well sorted.

---

* mm = $2^{-\emptyset}$

** Wentworth scale.

d. Skewness: -0.03 where
+0.3 to +1.00: strongly fine skewed
+0.1 to +0.3: fine skewed
-0.1 to +0.1: near symmetrical
-0.3 to -0.1: coarse skewed, etc.

The Reid-Bedford is, therefore, nearly symmetrical in distribution.

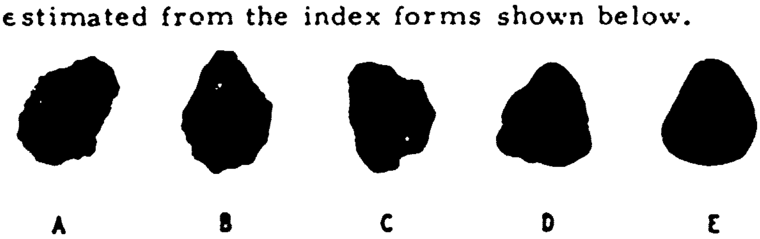
e. Kurtosis: 1.54. This value indicates a very leptokurtic curve where

$<0.67 \longrightarrow$ very platykurtic
0.67 to $0.90 \rightarrow$ platykurtic
0.90 to $1.11 \rightarrow$ mesokurtic
1.11 to $1.50 \rightarrow$ leptokurtic
1.50 to $3.00 \rightarrow$ very leptokurtic

Petrography

3. General. The sand was examined by both nonpolarizing binocular and polarizing microscopes. The nonpolarizing type facilitates the examination of the coarser particles, whereas the finer fractions require polarized light. In order to determine any variation in rounding and mineralogy with respect to grain size, the sample was sieved through the No. 35, 60, 120, 200, and 300 mesh sieves. Grain mounts using Lakeside 70 were prepared for the No. 120, 200, and 300 mesh splits and for the pan fraction.

4. Particle morphology (general). Two important elements of particle morphology are sphericity and roundness. Sphericity relates to a particle's equidimensionality, whereas roundness is a parameter that describes the extent of "rough edges" on the particle surface. These parameters are not necessarily related; a prismatic grain, for example, could have a highly rounded surface. Quantitative values may be determined for both sphericity and roundness, but this is a time-consuming task (especially for sphericity) and was not done here. Instead, roundness was estimated from the index forms shown below.



Roundness classes. A: Angular. B: Subangular C: Subrounded. D: Rounded. E: Well Rounded.

5. Preliminary examination of gross sample with nonpolarizing, binocular microscope. The sand consists predominantly of tan to light brown quartz sand. Two types may be distinguished as (a) a clear, unweathered, subangular type, and (b) a cloudy, less angular variety. These two types comprise roughly subequal proportions of the sample. Possibly some of the cloudy grains are feldspar. Moscovite mica is present and comprises less than 5 percent of the sample; the mica is considerably coarser (∽1.00 mm) than the accompanying quartz. Identifiable "heavy" minerals include tourmaline, garnet, and presumed amphibole-pyroxene minerals; no magnetic minerals were detected. The heavies are estimated to comprise no more than 1-2 percent of the total sample. The sample appears free of visible organic matter.

6. Examination of sieve splits. Examination of sieve splits consisted of the following sieves:

a. Sieve No. 35 (nonpolarizing). Predominantly subrounded to subangular grains of quartz; varieties include both clear and cloudy. The cloudy grains appear to have polished surfaces. Chert, ferromags, a siltstone rock fragment, and calcite concretions comprise approximately 1 or 2 percent of the split.

b. Sieve No. 60 (nonpolarizing). Very similar to sieve No. 35 except that there is an apparent slight increase in heavy mineral concentration (ferromags, garnet, etc.)

c. Sieve No. 120 (polarizing). Rounding: subangular; grain count revealed approximately 88.5 percent quartz and 11.5 percent feldspar. Although no other minerals were encountered in the count traverses, the nonquartz or feldspar content is probably around 1 percent or less.

d. Sieve No. 200 (polarizing microscope). Rounding: subangular; mineralogy is 92.3 percent quartz, 5.6 percent feldspar, and 2.1 percent opaques, mica, chert, and unknowns.

e. Sieve No. 300 (polarizing microscope). Rounding: subangular; mineralogy is 75.5 percent quartz, 15.3 percent feldspar, 4.6 percent opaques, 1.8 percent chert, 2.8 percent calcite, and unknowns.

f. Pan fraction (polarizing microscope). Rounding: subangular; mineralogy estimated to be 65 percent quartz, 25 percent feldspar, and 10 percent "heavies (opaques, zircon, rutile, etc.) and calcite.

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SUBJECT: Petrographic Examination of the Reid Bedford Model Sand

Mineralogical summary

7. Table 1 below summarizes the mineralogical composition of the sample and relates this to grain size.

Table 1

Mineralogical Composition

Sieve No.	Ø	mm	Fraction of Total Sample	Percent of Total Sample Quartz	Feldspar	Other*
35	+1.00	0.500	0.050	4.5	0.4	0.1
60	+2.00	0.250	0.450	40.5	3.2	1.4
120	+3.00	0.125	0.465	41.2	5.4	0.5
200	+3.75	0.074	0.021	1.9	0.1	tr
300	+4.40	0.046	0.002	0.2	tr	tr
Pan			0.012	0.8	0.3	0.1
		Totals	1.000	89.1	9.4	2.1

*Other includes calcite, mica, "heavies," and ferromags.

8. The mineralogy of the composite sample may be summarized as: quartz, 89 percent; feldspar, 9 percent; and other minerals, 2 percent. Although no detailed analysis was performed on the heavy mineral suite (specific gravity ≥ 2.8), the apparent low concentration of these minerals (< 2 percent) indicates that the assumed specific gravity of 2.65 is approximately correct.

Particle morphology

9. The degree of rounding is, in part, a function of size; ordinarily the coarser particles exhibit better rounding than the finer ones. This is the case with the Reid-Bedford. Although the coarser particles are classed as subangular to subrounded, the finer particles (less than 0.25 mm) are subangular. The overall classification is subangular to subrounded.

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SUBJECT: Petrographic Examination of the Reid-Bedford Model Sand

10. With respect to sphericity, the sample consists of considerable prismatic or tabular quartz grains, some of which exhibit sharp edges and conchoidal fracture surfaces. These features are more characteristic of the minus 0.25-mm fraction. The photomicrographs shown in figs. 1-3 illustrate particle morphology (Incls 1-3).

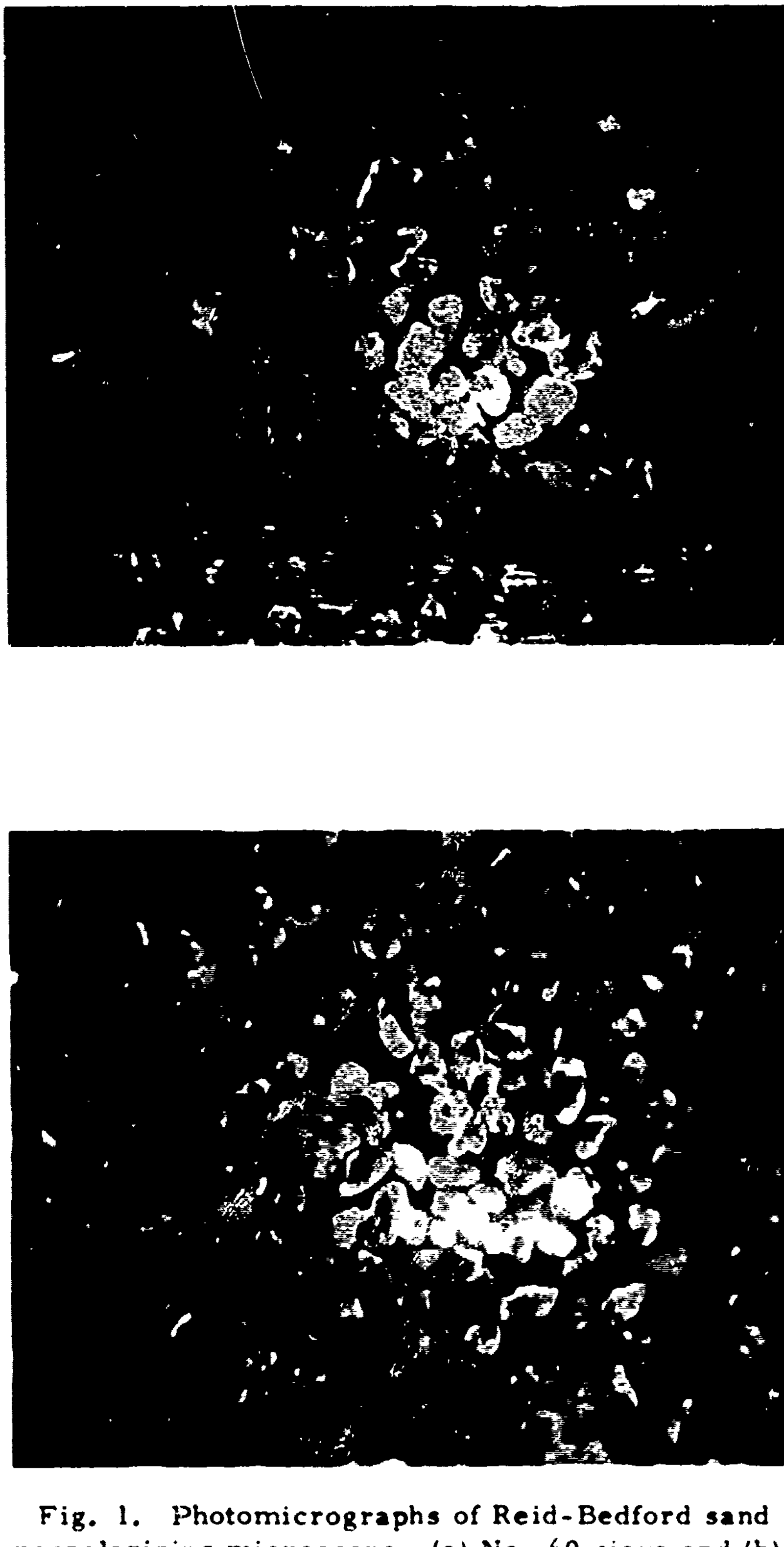
Conclusions and recommendations

11. The Reid-Bedford model sand is classified as: well to moderately well sorted, near symmetrical, very leptokurtic, medium to fine sand whose mineralogy consists of 89 percent quartz, 9 percent feldspar, and 2 percent calcite, ferromags, and "heavies." The rounding class is subrounded to subangular.

12. In order to more adequately determine the degree of rounding, it is recommended that scanning electron microscopy be performed on selected sieve splits in the future.

3 Incl
as

DAVID M. PATRICK
Research Geologist
Engineering Geology Division



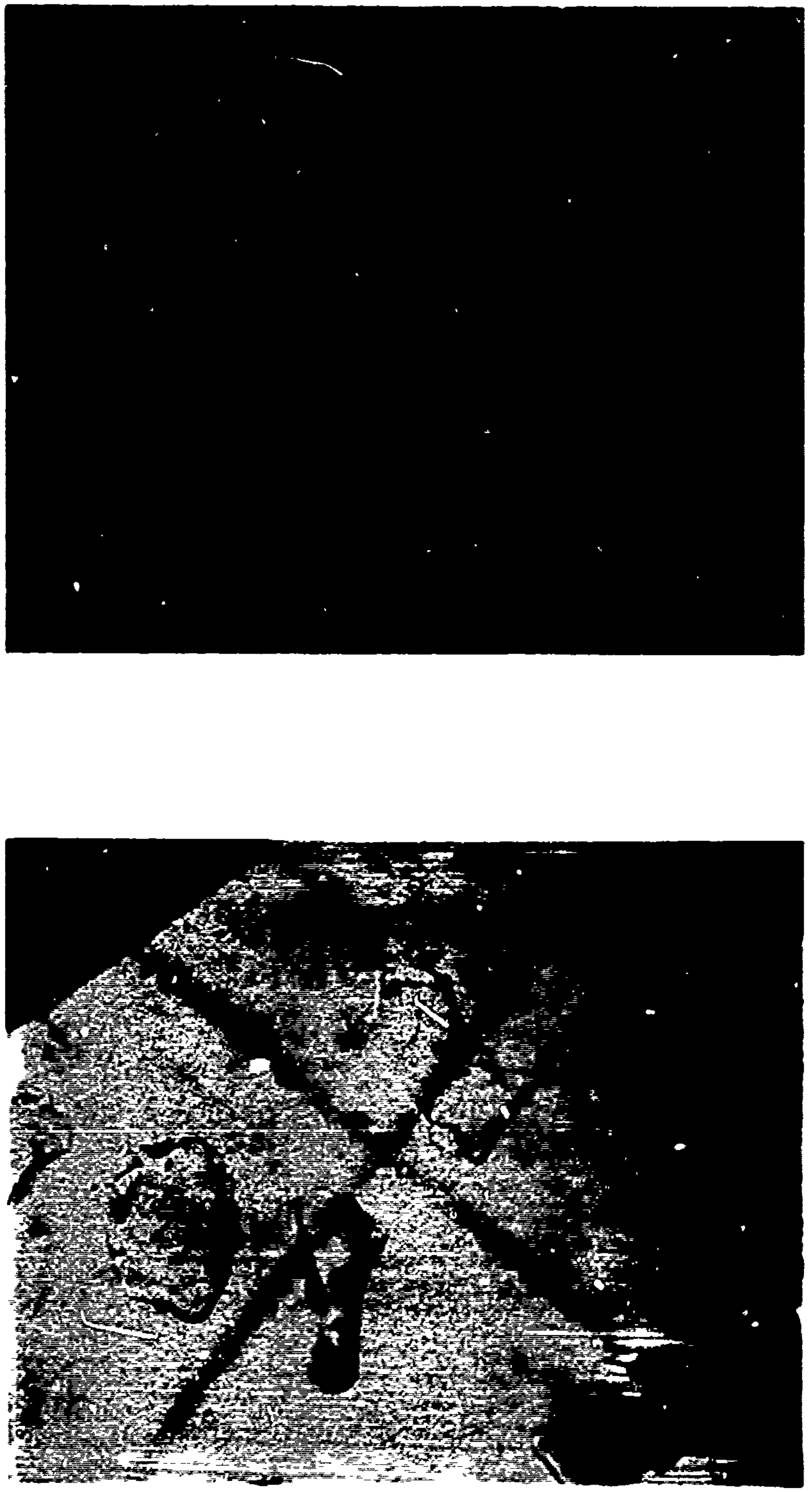
(a)

0.25 mm

(b)

0.125 mm

Fig. 1. Photomicrographs of Reid-Bedford sand
taken with nonpolarizing microscope: (a) No. 60 sieve and (b) No. 120 sieve.



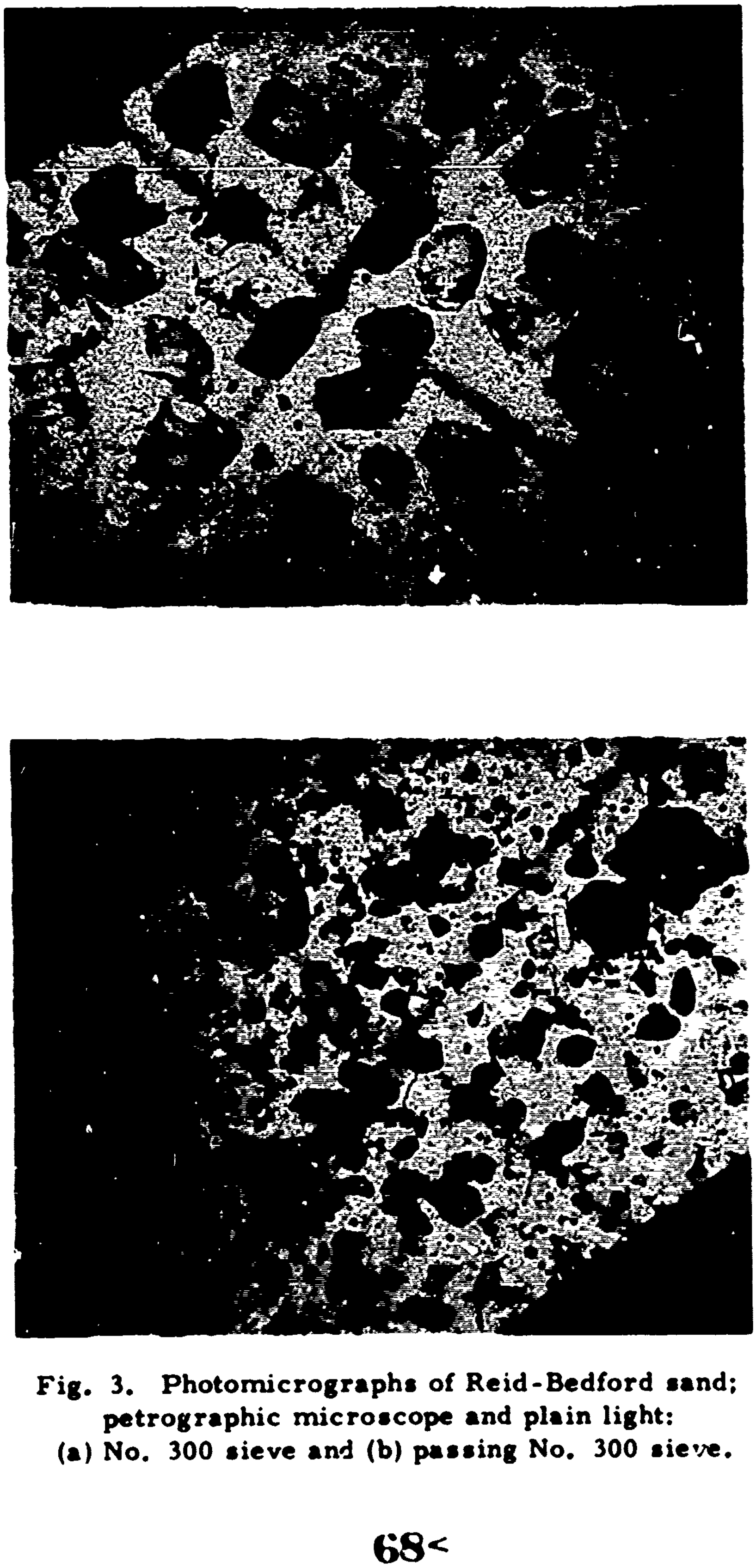
(a)

0.074 mm

(b)

0.074 mm

Fig. 2. Photomicrographs of Reid-Bedford sand, No. 200 sieve: (a) nonpolarizing microscope and (b) petrographic microscope, plain light.



(a)

0.046 mm

(b)

0.046 mm

Fig. 3. Photomicrographs of Reid-Bedford sand; petrographic microscope and plain light: (a) No. 300 sieve and (b) passing No. 300 sieve.

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Cooper, Stafford S

Laboratory investigation of undisturbed sampling of cohesionless material below the water table, by Stafford S. Cooper. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Research report S-76-1)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under CWIS 31145.

Includes bibliography.

1. Cohesionless soils. 2. Laboratory tests. 3. Sands. 4. Soil test specimens. 5. Undisturbed soil samples. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Research report S-76-1)

TA7.W34r no.S-76-1